7 Virtual Reality Simulators

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"Nothing is as powerful as an idea whose time has come" –
Victor Hugo, Histoire d'un Crime (The History of a Crime), 1877.

Take-Home Messages

- Virtual reality knee and shoulder arthroscopy simulators allow standardized, sustained, deliberate practice.
- Virtual reality simulators can facilitate self-directed learning and let individuals progress at an appropriate pace.
- Virtual reality simulators provide accurate performance tracking and detailed feedback to inform future training and highlight areas for improvement.

7.1 Definitions

Virtual reality (VR) is defined as the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment (Oxford English Dictionary 2014).

Fidelity refers to the extent to which a simulator reproduces the state and behavior of a real-world object. The more realistic it is, the higher the fidelity, and this is vital to the accurate representation of intraoperative techniques.

Haptic feedback is a method for sensory feedback that can provide a user with information regarding the contact of instruments with structures, as well as forces and possible injuries to be estimated. Haptic feedback consists of two modalities: kinesthesia and tactility.

Kinesthetic feedback, often referred to as *force feedback*, provides internal sensory information about position or movement of muscle, tendons, and bones through proprioception. Such feedback assesses both contour and stiffness of objects. Additionally, Golgi tendon organs and muscle spindles inform about applied force and opening angle of hands both applicable to arthroscopy and laparoscopy (Heijnsdijk et al. 2004).

Tactile feedback Tactility is the cutaneous perception of surface texture, pressure, heat, or pain through external contact with skin receptors. In open surgery, the surgeon relies on digital palpation to assess mechanical properties in addition

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to temperature and the shape of tissues. Tactile feedback may discriminate between tissue states such as trauma, degenerative change, and malignancy.

7.2 History of Electronic Flight Simulators

Major technological advances occurred during World War II (WWII), coupled with the development of analog computers, meaning that the technology now existed to calculate the flight equations necessary to simulate the response to aerodynamic forces rather than the mere physical representation of their effects. Approximately 10,000 simulators were used during WWII to train more than 500,000 pilots before proceeding to actual flight training or to fine-tune the skills of experienced pilots. Interestingly, the majority of German Luftwaffe bomber pilots would also have spent a minimum of 50 h in a Link Trainer (Chap. 6).

As technology advanced, the Curtiss-Wright Corporation was contracted by Pan American Airways to construct the first full aircraft simulator for the Boeing 377 Stratocruiser in 1943. Other airlines went on to purchase similar machines, but simulator evolution began to plateau over the next decade as it became clear that analog computers could not provide the desired fidelity or reliability.

7.3 History of Digital Simulators

These obstacles were overcome by the introduction of digital computers in the 1960s and 1970s. Concomitantly, motion systems were developed to provide six degrees of freedom. NASA undertook significant research into motion systems and created a Lunar Module simulator (a larger and more complex version of the original Link Trainer) to prepare for the first moon landing of 1969. When Buzz Aldrin piloted the Lunar Module down onto the surface of the moon, he said: "*Everything is A-OK. It throttles down better than the simulator*." The Apollo 11 crew had spent over 600 h in simulator training and the astronauts of the Apollo program had averaged approximately 936 h of simulator time each.

There was also a need for systems to provide *out-of-window* visual scenes in order to improve fidelity. The first computer-generated image (CGI) simulation systems were produced by the General Electric Company for the space program. Progress was rapid and closely linked to developments in digital computer hardware. The quality and content of the image display improved so significantly that it became possible for pilots to become familiar with routes through using the simulator. The International Air Transport Association (IATA) formed a Flight Simulator Technical Sub-Committee (FSTSC) in 1973 and set about developing the standards for simulation, and this allowed simulation to become a compulsory requirement for accreditation and completed the transfer of training and aircrew certification from the aircraft to the simulator.

Aircraft simulators nowadays typically cost between £20 and 30 million and are used 22 h a day with 2 h of downtime for maintenance. Pilots learning to fly a new aircraft typically undergo 2 weeks of *ground school* followed by 3–4 weeks of simulator training. The use of simulation has resulted in a decrease in the requirements for actual training hours on airplanes. Once accredited, pilots undergo simulator-based testing twice a year in order to maintain their licenses.

7.4 VR Simulation in Medicine

The aviation industry's experience with simulation dates back almost a century, and its success has resulted from the establishment of standards for data, design, modeling, performance, and testing, with international agreements for accreditation at defined levels of fidelity (Riley 2008). VR simulation in medicine has developed over the past two decades now in response to working hour restrictions for doctors, rising medicolegal compensation payments, and increasing focus on patient safety (McGovern 1994; Satava 1993, 1994). There is no substitute for sustained, deliberate practice. Without this there are problems with the retention of recently learned skills, and the longer the period they are not used, the greater the rate of decay (Kneebone et al. 2004). Simulation may then offer opportunities to support learning by allowing the practice and consolidation of clinical skills. There is growing evidence for simulation to be included as part of the surgical training curriculum, and it is recognized as a valuable means of practicing and improving laparoscopic skills (Aggarwal et al. 2007, 2008).

Many studies have been confined to the virtual world, but further work has shown that the effects of simulation-based training can cross over into the "real world." The use of a VR simulation-based curriculum has been shown to shorten the learning curve on laparoscopic procedures in the operating theatre (Aggarwal et al. 2008). Skills attained using the simulator can significantly improve performance in the *live* procedure (Seymour et al. 2002).

7.5 VR Simulation in Arthroscopy

The majority of orthopedic surgical procedures involve open surgery with complex anatomical and patient positioning factors that are not easily amenable to simulation. Arthroscopic procedures better lend themselves to simulation, with the conversion of three dimensions to a 2D screen easier replicated. As computer processing power has rapidly developed, the quality of graphics has facilitated realistic representations of arthroscopic procedures. The fidelity is further heightened by the use of instruments being used at a distance from the surgeon, out of the direct field of view.

Virtual reality simulators have developed as a means of addressing these issues. They have been used increasingly with time as they allow training in a safe, protected environment. Once trainees have been shown how to use the simulator, they can undertake training at their own pace at a time of their choice to achieve personal goals (Michelson 2006).

The first arthroscopic VR simulator was described in Germany in 1995 as a result of a collaboration between traumatologists and computer graphics scientists (Ziegler et al. 1995). In 1996 the American Academy of Orthopedic Surgeons (AAOS) evaluated VR technology as a means of learning and maintaining surgical skills and felt that it was too early to commit the substantial resources required (Mabrey et al. 2000; Poss et al. 2000). However, the following year, the American Board of Orthopedic Surgery (ABOS) funded the development of a prototype VR knee simulator with three aims:

- That it be embraced by the entire orthopedic community
- That the tool must be valid and reliable
- That surgeons must have experience with the simulator and have confidence that it is a realistic and useful surrogate for actual operative surgery

After this, other computer science groups from all over the world have taken initiatives to design virtual reality environments of the knee (Gibson et al. 1997; Heng et al. 2004, 2006; Hollands and Trowbridge 1996; Megali et al. 2002; Ward et al. 1998) by the application of volume rendering techniques (Gibson et al. 1997), object deformation modeling techniques for collision detection (Sherman et al. 1999, 2001; Ward et al. 1998), and computer graphics techniques to guide a trainer through exercises (Megali et al. 2002, 2005). All these initiatives have not let to commercialization.

Generally, VR arthroscopy simulators comprise a computer and screen which present the virtual world. The instruments are designed to recreate the look, feel, and/or functionality of those used in the operating theatre. These physical devices are represented on the screen and thus can be used to interact with the virtual environment. Instruments that can be recreated include cameras, probes, punches, chondral picks, and shavers. The visual graphics used by VR simulators have improved exponentially as computing power has developed, but also key is the feeling of touch, and knowing where the structure at the end of the probe is soft or hard plays an important role. That is why in general VR simulators also have a synthetic shoulder or knee joint model that can be manipulated and into which instruments can be inserted through predefined portals. These instruments can be used to manipulate virtual tissues and organs, and there may be visual feedback through the visible deformity of tissues or force feedback through a haptic device.

In minimally invasive surgery, instruments connect the hands with the tissues and act as the conduits for conveying information about the nature of intra-articular structures. Insufficient visual detail can lead to misidentification of anatomy and the increased likelihood of adverse events (Zhou et al. 2008). In the remainder of this section, several VR simulators are discussed that reflect the overall development and availability of arthroscopic VR simulators.

7.6 SKATS VR Simulator

Haptic feedback can be active or passive. The Sheffield Knee Arthroscopy Training System (SKATS) was initially designed as a cost-effective PC-based knee arthroscopy simulator consisting of a hollow plastic leg, replica surgical instruments, and a monitor displaying the internal view of the knee joint (McCarthy et al. 2006; McCarthy and Hollands 1998). A 3D computer-generated environment provided a real-time, interactive simulation of the tissue with the screen responding to the user as bimanual arthroscopic tasks are performed and the visual image is changed correspondingly. Research has shown that the effectiveness of a simulator is based on visual, haptic, and proprioceptive information. Evaluation of the original system by surgeons demonstrated severe acceptability issues as the instruments would pass through solid structures, and this is likely to affect skill acquisition and disrupt the level of immersion in the task due to the lack of reality (Moody et al. 2003).

Arthroscopy is a bimanual task that uses haptic cues for a range of tasks, and adding this to this machine would require two four-degree-of-freedom haptic devices to apply reactionary forces in response to contact with a variety of knee structures and yet still fit within a fully manipulable physical limb model. It was therefore decided to develop this further by adding passive haptics (tactile augmentation) (Moody et al. 2008). A more realistic leg was used containing solid femur and tibia to create a mixed reality environment where physical contact is felt when touching the bone.

The validation results obtained when passive haptic feedback (resistance provided by physical structures) was provided indicate that the SKATS had construct, predictive, and face validity for navigation and triangulation training. Feedback from questionnaires completed by orthopedic surgeons indicated that the system had face validity for its remit of basic arthroscopic training. There was a desire to include haptic feedback, though a formal task analysis demonstrated that many of the core skills for trainees to learn when navigating a knee arthroscopically did not require active haptics and though the feedback highlighted the need for the menisci and ligaments to provide haptic feedback in addition to the bone. Further development of the SKATS ceased in 2004, and this system was not produced for sale.

7.7 SIMENDO Arthroscopy™

The SIMENDO Arthroscopy™ (Simendo, Rotterdam, the Netherlands, www.simendo.eu) is one of the few arthroscopic VR simulators that solely focuses on training of eye-hand coordination. The system consists of a Notebook computer and a console with three devices: a camera, a probe, and a foot with part of the lower leg (Fig. 7.1). The focus on eye-coordination training is prominently expressed in their exercises *4 Boxes* and *6 Boxes*, which take place in an entirely virtual world that does not represent a human joint and focuses solely on correct camera orientation. The VR simulator does not provide any active haptic device, so trainees rely solely on their visual feedback. Target users are residents that have no arthroscopic experience. The simulator can also be connected to the Internet, where training progress is documented and can be viewed by supervising surgeons.

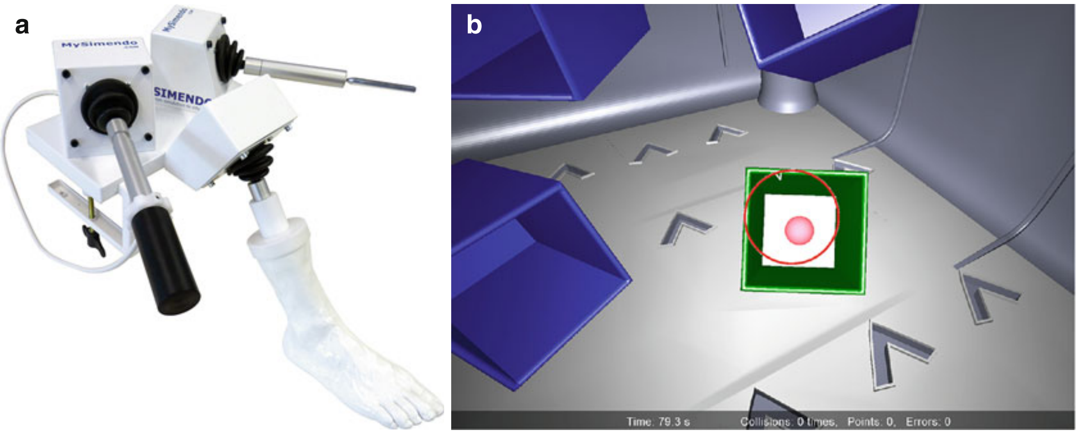

Fig. 7.1 (**a**) SIMENDO Arthroscopy™ simulator. (**b**) Screenshot from the virtual world of the *Boxes* exercises. The ball in a box needs to be touched with the camera tip (© Simendo, 2014. Reprinted with permission from www.simendo.eu)

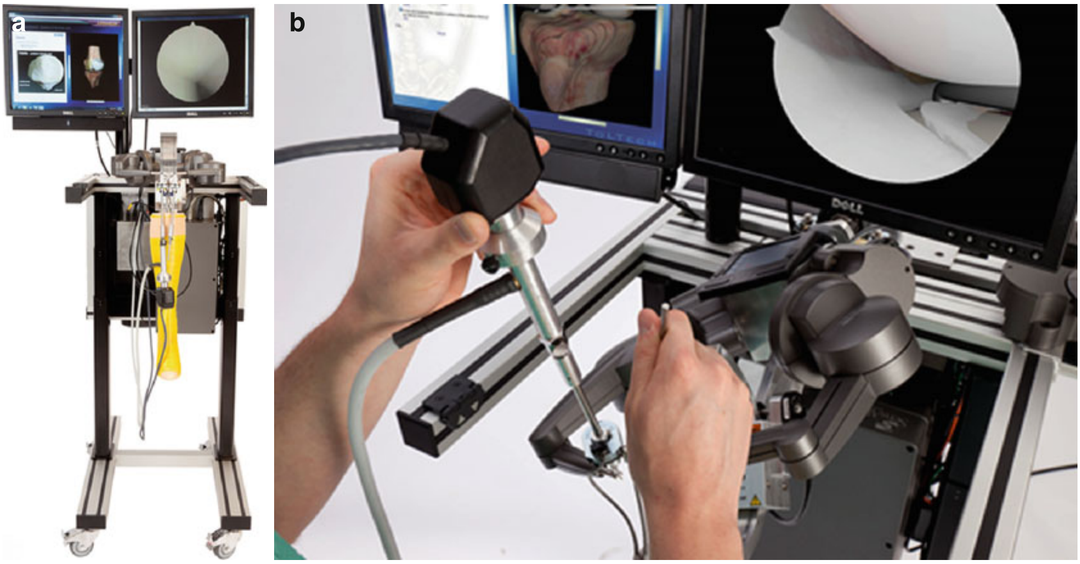

Fig. 7.2 (**a**) The Knee Arthroscopy Surgical Trainer (KAST) named ArthroSim™. (**b**) Close up of the ArthroSim controls with the arthroscope in the left hand and the probe in the right

7.8 Knee Arthroscopy Surgical Trainer: ArthroSim*™*

The Knee Arthroscopy Surgical Trainer (KAST) was developed by the AAOS Virtual Reality Task Force in collaboration between the ABOS, the Arthroscopy Association of North America (AANA), and Touch of Life Technologies (ToLTech, Colorado, USA, www.toltech.net) (Fig. 7.2).This platform was subsequently developed to add shoulder arthroscopy and has been renamed the ArthroSim*™* Arthroscopy Simulator. This machine uses data from the Visible Human Project and has a computer hardware component supported by proprietary software and a didactic component delivered on one of two monitors positioned in front of the trainee. The core of the hardware component is a pair of high-fidelity active haptic devices (Geomagic Touch, North Carolina, USA [formerly Sensable Phantom Omni]) that monitor the position of the instruments to recreate the feel of the arthroscope and the probe within the knee.

The software represents and replicates the visual, mechanical, and behavioral aspects of the knee while task-oriented programs monitor and record performance metrics. This includes moderating the haptic interface and simultaneously executing a collision detection algorithm that prevents the instruments from moving through solid surfaces. The two-hand haptic device provides 4 degrees of freedom (DOF). The first three DOFs with force feedback consist of pitch, yaw, and insertion that enable the instrument to move in a way similar to a real arthroscope. The fourth rotational DOF is without force feedback to enable surgeons to look around the immediate vicinity of the 30° arthroscope tip, and there is also force feedback when there is a collision or when handling soft tissues.

There is a dual monitor system where the right screen displays the intra-articular image and the left screen displays the "Mentor." This provides a training program based on a curriculum developed by the AAOS. It uses movies, images, animations, and texts to outline the steps of each procedure. Trainees must achieve proficiency and score 100 % in each step before finally performing the entire procedure unaided within a community standard time.

However, the ArthroSim*TM* is currently limited to diagnostic procedures only though there are plans to develop therapeutic tasks. It is currently undergoing validation studies at eight orthopedic residency programs in the USA and the results are awaited.

7.9 ARTHRO Mentor*TM*

The ARTHRO Mentor*TM* (Simbionix, Cleveland, Ohio USA, www.simbionix.com) uses the same pair of Geomagic Touch haptic devices for active feedback (Fig. 7.3). It was initially created and marketed as the Insight ArthroVR*TM* arthroscopy simulator (GMV, Madrid, Spain) but was subsequently bought and further developed by the company Simbionix. It consists of a synthetic shoulder or knee model attached to a platform incorporating two haptic devices, a computer and screen.

Fig. 7.3 ARTHRO Mentor™ VR simulator for knee and shoulder arthroscopy

The ARTHRO Mentor*TM* provides a sequence of training modules to help trainees develop the necessary skills to perform arthroscopic surgery. It focuses on the identification of anatomical structures, navigation skills, triangulation and depth perception, and instrument handling skills. It displays both healthy and pathological states and incorporates diagnostic and therapeutic procedures for the shoulder and knee. Similar to the other available simulators, it provides detailed and exportable feedback reports covering the distance covered by the camera and instruments, time taken, and the smoothness and efficiency of movements. Feedback is one area where VR simulators excel, and immediate visual feedback of multiple performance metrics highlights their educational potential (Howells et al. 2008b). Trainees can closely monitor their performance through variables such as time taken, path length, and number of hand movements. These metrics have been proven to correlate with surgical proficiency and thus provide valuable feedback (Datta et al. 2001; Howells et al. 2008a).

All of the commercially available highlighted simulators allow trainees to be provided with individualized and customizable learning programs. The ARTHRO Mentor is linked to *MentorLearn*, a Web-based simulator management program to help facilitate this.

7.10 VirtaMed ArthroS™ Simulator for Knee and Shoulder Arthroscopy

A new commercially available arthroscopy simulator has recently come to the market that is also centered on passive haptics (Fig. 7.4).

The VirtaMed ArthroS™ for knee and shoulder arthroscopy (VirtaMed AG, Zurich, Switzerland, www.virtamed.com) is the only available VR simulator to use a modified actual arthroscope and modified authentic instruments in order to add to fidelity and allow trainees to familiarize themselves with the equipment. It also has inlet and outlet valves for fluid handling and replicates the poor view that is encountered when this is not managed appropriately. Cameras with 0, 30, and 70° are provided, along with a probe, grasper, punch, and shaver. A synthetic knee or shoulder model is added, and the knee can be subjected to varus and valgus stresses to open up the joint compartments as required, and the shoulder model can be placed in a lateral decubitus or beach chair position.

Didactic tutorials allow trainees to use the machine independently and facilitate self-directed learning. There are guided modules for learning basic skills, modules for diagnostic arthroscopy requiring use of the probe, and modules for therapeutic arthroscopy requiring the use of the grasper, punch, or shaver.

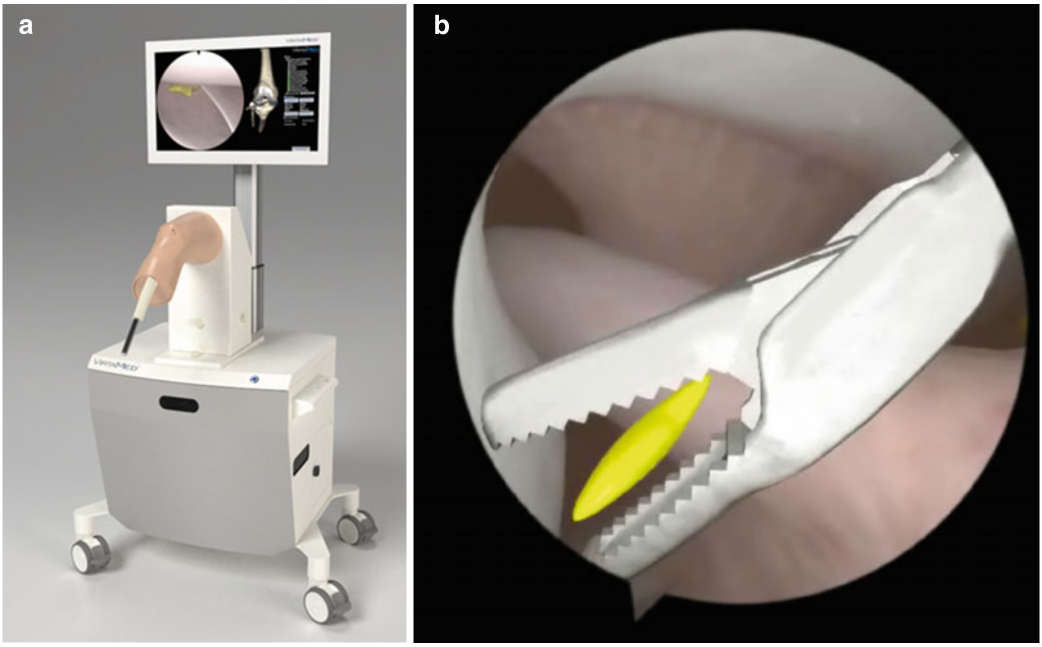

Fig. 7.4 (**a**) VirtaMed ArthroS™ for knee arthroscopy. (**b**) Training exercise using the VirtaMed ArthroS™ for knee arthroscopy. (**c**) VirtaMed ArthroS™ for shoulder arthroscopy. (**d**) Removal of loose bodies on the VirtaMed ArthroS™ for shoulder arthroscopy

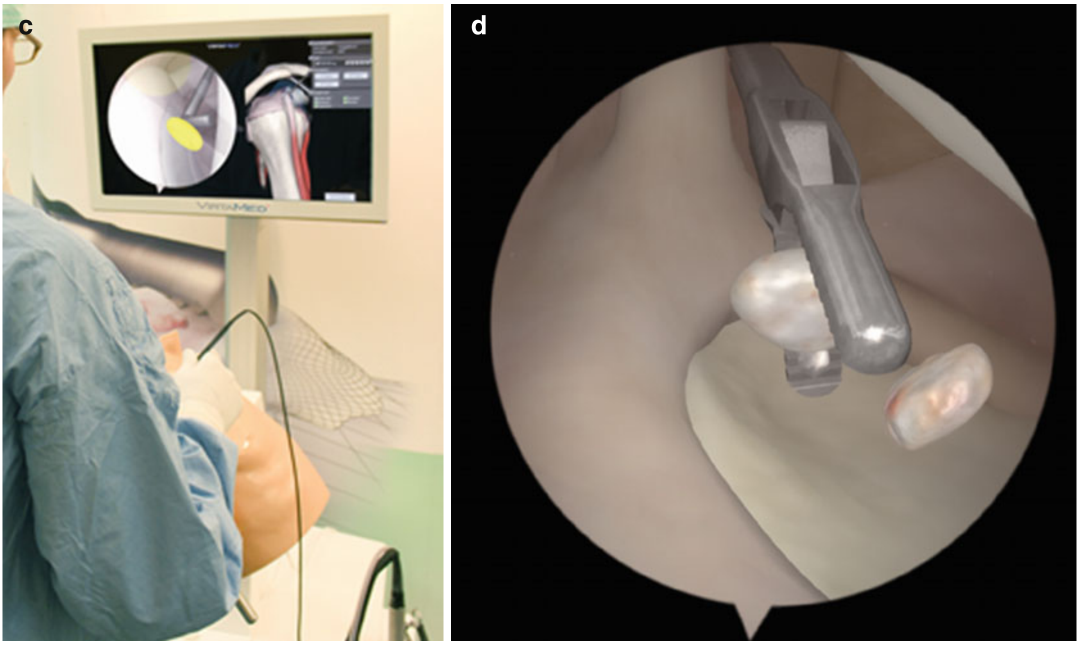

Fig. 7.4 (continued)

7.11 Discussion

VR arthroscopy simulators have repeatedly been shown to be acceptable, realistic, and effective at subjectively distinguishing between individuals of different levels of clinical experience and skill. Training on a simulator results in significant improvement in arthroscopic skills, and individuals who continue with their clinical training improve concomitantly in their simulator performance. VR simulators avoid the ethical and storage issues associated with cadavers. Cadavers require high maintenance, are not readily available, and can only be used a limited number of times, and the quality is dependent on the embalming technique employed. Synthetic models meanwhile are not reusable, can oversimplify the task, can cause significant mess, are resource and staff intensive, and have low face validity. While some VR simulators can be expensive and require periodic maintenance, this can often be done remotely online. They can be used repeatedly with no consumable parts and require less human resources. They are also compact and do not take up a significant amount of space. They can display a range of pathology and have no ethical constraints. VR simulators allow standardized, repeated practice that has high validity and reliability. They are more appropriate to self-directed learning, and trainees can progress at their own pace and at a time of their choice to achieve personal goals without the need for a senior surgeon to be present, unlike other forms of simulation-based training (Michelson 2006).

However, the current VR simulators are not without their limitations. One criticism of VR simulators has been the lack of realistic tissue behavior (Dankelman 2007). Surgeons value haptics in surgical simulators, and this has been addressed to some degree by improvement in collision detection and improved haptic feedback. This was seen with the (discontinued) Procedicus Virtual Arthroscopy trainer (Mentice Inc., San Diego, USA) which provided haptic feedback and was rated highly by participants because it made the experience of shoulder and knee procedures more realistic and showed high levels of internal consistency and reliability (Modi et al. 2010).

VR simulators are most appropriate for trainees needing to practice basic arthroscopic tasks and do not faithfully simulate the more complex tasks. There is little published research on the current commercially available simulators and there has not been any evidence of the ability of VR simulator-based training to improve arthroscopic performance in the operating theatre. Further crossover studies are needed with longitudinal follow-up of trainees undergoing VR simulation-based training to fully understand the benefits to patients. It is accepted though that simulator training can shorten the time it takes for trainees to acquire basic skills in theatre, and this has universal advantages, for trainees, trainers, institutions, and, most importantly, patients. The use of VR simulation can be an effective way for junior orthopedic trainees to quickly attain the basic technical skills specific to orthopedic surgery. Simulation-based training can cause a "right shift" along the learning curve for more efficient training with real-world improvements (Ahlberg et al. 2007; Larsen et al. 2009; Seymour et al. 2002).

In recent years, there has been a drive to integrate simulation into surgical training programs and an understanding of the need to develop validated curricula (Aggarwal et al. 2004). It has been shown that simulators can be used to create a graduated laparoscopic training curriculum and this work has been extended to create an evidence-based virtual reality training program for novice laparoscopic surgeons (Aggarwal et al. 2006a, b).

There is growing evidence for simulation to be formally integrated into the orthopedic curriculum. It should however be placed in the context of traditional training methods and regarded as a means rather than an end in itself.

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