SIMULATION-BASED TRAINING FOR ORTHOPEDIC RESIDENTS: IMPACT ON SURGICAL CONFIDENCE AND SKILL ACQUISITION

Mukhammadiyev Sobirjon Uchkunjon ugli
Traumatology and Orthopedics, FMIOPH, Fergana, Uzbekistan
mukhammadiyev95@gmail.com
Nishanov Eshonkhoja Khamedkhoja ugli
Traumatology and Orthopedics, FMIOPH, Fergana, Uzbekistan
eshonxojanishonov@gmail.com
Eminov Ravshanjon Ikromjon Ugli
Faculty and Hospital Surgery Department, FMIOPH, Fergana, Uzbekistan

Abstract: Simulation-based training has revolutionized orthopedic education by providing realistic, risk-free environments for surgical practice. This article reviews current technologies such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and haptic-based systems used to train orthopedic residents. These tools improve psychomotor skills, surgical confidence, and procedural accuracy. Despite rapid technological advancement, challenges such as cost and curricular integration remain. Structured simulation programs hold promise for the future of surgical education.
Keywords: simulation, orthopedics, training, technology, surgery

Аннотация: Обучение на основе симуляторов произвело революцию в ортопедическом образовании, обеспечивая реалистичную и безопасную среду для практики хирургических навыков. В статье рассматриваются современные технологии, такие как виртуальная реальность (VR), дополненная реальность (AR), смешанная реальность (MR) и системы с тактильной обратной связью, используемые в подготовке ортопедов. Эти технологии улучшают психомоторные навыки, уверенность хирургов и точность операций. Несмотря на достижения, остаются проблемы интеграции в учебные программы и высокая стоимость. Структурированные симуляционные курсы имеют большое будущее в хирургическом обучении.
Ключевые слова: симуляция, ортопедия, обучение, технологии, хирургия

Annotatsiya: Simulyatsiyaga asoslangan treninglar ortopediya ta’limida inqilobiy o‘zgarishlar olib keldi. Ular jarrohlik amaliyotini xavfsiz va real muhitda mashq qilish imkonini beradi. Ushbu maqolada ortopediya rezidentlarini o‘qitishda qo‘llaniladigan Virtual Haqiqat (VR), Kengaytirilgan Haqiqat (AR), Aralash Haqiqat (MR) va haptik tizimlar haqida so‘z boradi. Bu texnologiyalar psixomotor ko‘nikmalar, jarrohlik ishonchi va aniqligini oshiradi. Ammo yuqori xarajatlar va o‘quv dasturlariga to‘liq integratsiya kabi muammolar mavjud. Tuzilgan simulyatsiya dasturlari kelajakda jarrohlik ta’limining ajralmas qismiga aylanishi kutilmoqda.
Kalit so‘zlar: simulyatsiya, ortopediya, ta’lim, texnologiya, jarrohlik

Introduction

Simulation-based training for orthopedic residents employs a variety of simulators and technologies, each offering unique advantages and addressing different aspects of surgical education. Virtual Reality (VR) and Mixed Reality (MR) environments are prominently used, leveraging platforms like HTC Vive™ and Microsoft HoloLens™ to create immersive training experiences. These technologies allow residents to practice procedures such as the Less Invasive Stabilization System (LISS) plating surgery and Condylar plating surgery, which are crucial for treating femur fractures[1] [2] [3]. The integration of haptic feedback in simulators further enhances the realism by providing tactile sensations, which are essential for developing the psychomotor skills necessary for orthopedic surgery[2] [9]. Additionally, the use of green screen technology in MR environments enables interaction with both virtual and real-world objects, offering a comprehensive training experience[1] [3]. The Internet of Medical Things (IoMT) and Next Generation Internet technologies facilitate the development of network-based simulators, allowing for distributed and collaborative training environments that are accessible 24/7[3] [10]. Despite the technological advancements, the focus of many studies remains on validating these simulators rather than integrating them into formal curricula, highlighting a need for curricular development that aligns with educational frameworks like Kern's[4]. Moreover, the use of physical simulators, such as cadavers and models, continues to play a role, particularly in arthroscopy training, where hybrid simulators combine VR with physical components to provide realistic tactile feedback[7]. The evolution of orthopedic training methodologies, including the use of low-cost modules and motion tracking, reflects a shift towards more accessible and standardized training solutions[5] [6]. Overall, the diverse array of simulators and technologies underscores the potential of simulation-based training to enhance the surgical skills of orthopedic residents, although further integration into structured educational programs is necessary to maximize their impact[8].

Virtual Reality (VR) Simulators

Virtual Reality (VR) simulators are among the most widely used tools in orthopedic training. These systems provide an immersive environment where residents can practice surgical procedures without the risk of patient harm. VR simulators are further categorized into two types:

a. Desktop VR Simulators

- Description: These are non-immersive systems that use a computer, video screen, and a joint model. They allow residents to practice using various instruments and provide haptic feedback. Innovative software enables multiple training programs, offering precise performance feedback [1] [2].
- Example: The ARTHRO Mentor (Symbionix) and ArthroS (VirtaMed) are examples of desktop VR simulators used for arthroscopic training [14].

b. Immersive VR Simulators

- Description: These systems use head-mounted displays (HMDs) to create a fully immersive environment. They are particularly effective for complex procedures like hip arthroscopy and total hip arthroplasty. Studies have shown that skills learned on immersive VR simulators can be successfully transferred to real clinical scenarios [3] [9].
- Example: The PrecisionOS simulator is an immersive VR system used for training in hip arthroscopy [3].

Augmented Reality (AR) and Mixed Reality (MR) Simulators

Augmented Reality (AR) and Mixed Reality (MR) technologies are gaining traction in orthopedic training. These systems combine virtual and real-world elements to enhance surgical planning and education.

a. Augmented Reality (AR)

- Description: AR overlays digital information onto the real world, enabling surgeons to visualize patient-specific anatomy in real-time. This technology is particularly useful for preoperative planning and intraoperative navigation [5] [6].
- Example: Microsoft HoloLens is used to create hybrid simulators for orthopedic open surgery, combining AR with physical models [15].

b. Mixed Reality (MR)

- Description: MR allows interaction between virtual and real-world objects in real time. It is often used in hybrid simulators to create a more dynamic training environment [16] [18].
- Example: A mixed-reality simulator for Condylar plating surgery uses greenscreen technology to merge virtual and physical elements [16].

Hybrid Simulators

Hybrid simulators combine physical models with virtual or augmented reality elements to create a more realistic training experience.

- Description: These systems use patient-specific anatomical models created from imaging data (e.g., CT scans) and integrate them with virtual content. They are particularly useful for procedures like hip arthroplasty [15].
- Example: The Microsoft HoloLens-based hybrid simulator for hip arthroplasty combines physical synthetic bones with virtual anatomical models [15].

4. Physical and Synthetic Simulators

Physical and synthetic simulators are non-digital tools that replicate real-world surgical environments. They are often used in conjunction with virtual technologies.

- Description: These simulators use synthetic bones or cadaveric models to mimic surgical scenarios. They are ideal for training in procedures like thoracolumbar pedicle screw placement and knee arthroplasty [11] [12].
- Example: Synthetic spine models are used in simulation training for spinal instrumentation placement [11].

Digital Twins and Surgical Digital Twins (SDTs)

Digital twins are virtual replicas of real-world objects or environments. In orthopedic training, they are used to create high-fidelity surgical environments for preoperative planning and simulation.

- Description: Surgical Digital Twins (SDTs) are dynamic 3D models that replicate the entire surgical scene, including anatomy, instruments, and the surgeon's movements. They are integrated with VR systems like SurgTwinVR for immersive training [4].
- Example: SurgTwinVR is a VR application that immerses users in an SDT for surgical education [4].

Haptic-Based Simulators

Haptic-based simulators focus on providing tactile feedback, which is essential for mastering surgical techniques.

- Description: These systems use haptic devices to simulate the feel of surgical instruments and tissues. They are particularly useful for training in minimally invasive procedures like arthroscopy [3] [17].
- Example: The haptic-based simulator for Less Invasive Stabilization System (LISS) plating surgery provides realistic feedback for femur fracture repair [17].

Network-Based and Online Simulators

Advances in internet and networking technologies have enabled the development of online simulators that can be accessed remotely.

- Description: These systems allow residents to train anytime and anywhere, making them ideal for standardized curriculum-based training. They often incorporate haptic feedback and immersive environments [17] [20].
- Example: A standalone online haptic-based simulator for LISS plating surgery is accessible to residents via next-generation internet technologies [17].

Multi-Modality Educational Workshops

These workshops combine multiple simulation technologies and educational methods to provide comprehensive training.

- Description: They often include VR simulations, saw-bone models, tutorials, and case-based discussions. These workshops are designed to improve understanding of surgical principles and procedures [12].
- Example: A multi-modality "Bootcamp" for total knee arthroplasty (TKA) training includes VR simulation, saw-bone exercises, and case-based discussions [12].

Cyber-Human Frameworks

These frameworks integrate virtual and physical systems to create advanced training environments.

- Description: They use information-centric systems engineering (ICSE) principles to design simulators that combine haptic feedback, immersive VR, and real-time data analysis. These systems are particularly useful for complex procedures like femur fracture stabilization [20].
- Example: A cyber-human framework for LISS plating surgery uses haptic-based and immersive VR systems to train residents [20].

Table: Comparison of key simulators and technologies

Simulator/Technology	Purpose	Key Features	Citation
Desktop VR Simulators	Arthroscopic training	Computer-based, haptic feedback, multiple training programs	[1] [2] [14]
Immersive VR Simulators	Complex procedures like hip arthroscopy	Head-mounted displays, realistic environments, skill transfer to real surgeries	[3] [9]
Hybrid Simulators	Combines physical and virtual elements for realistic training	Patient-specific models, virtual content integration	[15]
Haptic-Based Simulators	Minimally invasive procedures like arthroscopy	Tactile feedback, realistic instrument handling	[3] [17]
Digital Twins (SDTs)	Preoperative planning and immersive training	High-fidelity 3D models, integration with VR systems	[4]
Multi-Modality Workshops	Comprehensive surgical education	VR simulation, saw-bone models, case-based discussions	[12]

Conclusion

Simulation-based training in orthopedics has evolved significantly with the integration of advanced technologies like VR, AR, MR, and digital twins. These tools provide residents with a safe and efficient way to acquire and refine surgical skills. While VR and immersive technologies dominate the field, hybrid and haptic-based systems are also gaining popularity. Despite their benefits, challenges such as high costs, technical limitations, and the need for further validation remain. As technology advances, these simulators are expected to play an even greater role in shaping the future of orthopedic surgical training.

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