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MIXED REALITY IN SURGICAL MECHATRONICS: INNOVATIONS AND CHALLENGES IN BIOENGINEERING EDUCATION AND CLINICAL PRACTICE

REALIDAD MIXTA EN MECATRÓNICA QUIRÚRGICA: INNOVACIONES Y RETOS EN LA EDUCACIÓN EN BIOINGENIERÍA Y PRÁCTICA CLÍNICA

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ABSTRACT

Introduction: Mixed reality (MR), a combination of augmented reality (AR) and virtual reality (VR), has emerged as a key tool in surgical mechatronics, improving precision and visualization in clinical procedures. **Methods:** This study presents a literature review of recent MR advances from the Scopus database, taking into account its impact on surgery and medical education. Technologies such as Microsoft HoloLens and Magic Leap, as well as neurosurgery and orthopedic simulators, are reviewed. **Results:** MR enhances surgical precision and reduces operating times, with an average decrease from 121.34 to 97.62 minutes. Despite its potential, challenges include discomfort from prolonged device use and low battery autonomy. **Conclusions:** MR has the potential to transform surgery and medical education; however, its widespread adoption will depend on overcoming technological and financial barriers, especially in Latin America, where infrastructure is still limited.

Keywords: Surgery; Mechatronics; Virtual reality; Medical education; Bioengineering. (Source: MESH-NLM)

RESUMEN

Introducción: La realidad mixta (RM), combinación de realidad aumentada (RA) y virtual (RV) ha emergido como una herramienta clave en la mecatrónica quirúrgica y ha mejorado la precisión y la visualización en procedimientos clínicos. **Métodos:** Este estudio presenta una revisión de literatura de los recientes avances en RM, en la base de datos Scopus y se ha tomado en cuenta el impacto en cirugía y la enseñanza médica. Se revisan tecnologías como Microsoft HoloLens y Magic Leap, así como simuladores de neurocirugía y ortopedia. **Resultados:** La RM mejora la precisión quirúrgica y reduce los tiempos operativos, que baja de 121.34 a 97.62 minutos en promedio. A pesar de su potencial, se enfrentan desafíos como la incomodidad del uso prolongado de dispositivos y la baja autonomía de las baterías. **Conclusiones:** La RM puede transformar la cirugía y la educación médica, sin embargo, su adopción masiva dependerá de la superación de barreras tecnológicas y financieras, especialmente en Latinoamérica, donde la infraestructura aún es limitada.

Palabras clave: Cirugía; Mecatrónica; Realidad virtual; Enseñanza médica; Bioingeniería. (Fuente: DeCS-BIREME)

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INTRODUCTION

Mixed reality (MR) lies between augmented reality (AR) and virtual reality (VR), combining elements of both to offer a more advanced interactive experience. VR creates fully virtual and immersive environments that can engage multiple senses, while AR overlays virtual data onto the real-world environment, without deep interaction [1]. In contrast, MR integrates virtual data into the real environment, allowing real-time interaction, providing a more immersive and functional experience[2,3], as shown in Table 1. Devices such as HoloLens enable the visualization of three-dimensional data during surgical procedures without disrupting the workflow, although they face challenges such as the need for specialized software and potential side effects for users [4,5] (Figure 1). Globally, the majority of studies have been conducted in the United States (1883), followed by England (677), Canada (600), Germany (509), and Italy (444), with Peru falling below 100 studies [6]. Despite these challenges, MR has the potential to transform surgery and medical education, improving precision and real-time decision-making.

Figure 1. Proposal for future collaborative implementation of brain surgery, utilizing virtual reality glasses to visualize the morphology of the organ. Original contribution.

Table 1. Comparison of mixed reality (MR) technologies in surgery.

Characteristic	Augmented Reality (AR)	Mixed Reality (MR)
Interaction	Real-time direct or indirect view of a physical real-world environment enhanced/augmented by computer-generated information[7,8].	It integrates physical and digital environments, allowing continuous interaction between them. It helps design and evaluate how users interact with physical and digital elements simultaneously[9].
Devices	Phones, tablets, AR glasses, headsets like HoloLens[10].	Head-mounted display, wearable display devices, monitor-based and projection-based screens[11].
Applications	Advertising and commercial, entertainment and education, medicine, and mobile applications for iPhones[12].	Education with integrated learning, collaborative design with virtual models in real environments[11], neurosurgery, maxillofacial surgery, general surgery[13].

In this context, computer-assisted surgery (CAS) emerges[14,15], integrating mechatronic systems with MR to provide surgeons with training without compromising patient safety [16], as seen in robotic surgery [17], neurosurgery, orthopedics, laparoscopy, endoluminal intervention with flexible robots, the use of medical capsules, and unconnected micro/nano robots, among others, demonstrating significant progress in enhancing precision and minimizing invasiveness [18]. (Figure 2). In 2009, Mauro et al. developed an MR neurosurgical microscope for training and intraoperative purposes, with realistic simulation (visual and haptic) for palpation of low-grade gliomas, along with augmented reality stereoscopic visualization of 3D data relevant for safe surgical movements in image-guided interventions [19-21].

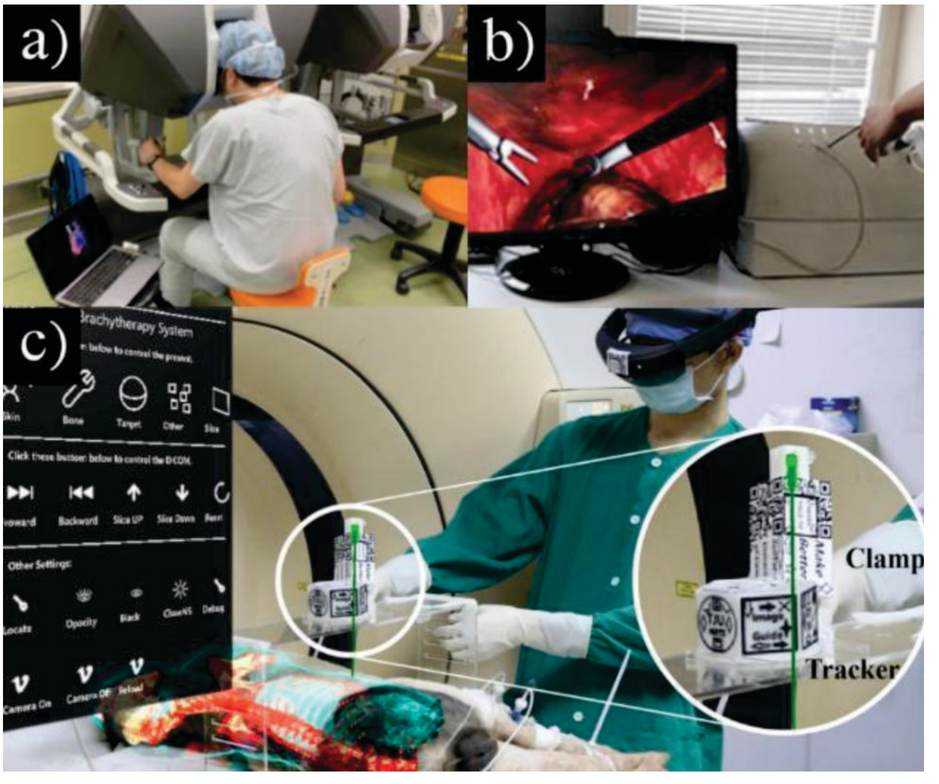

Figure 2. (a) Visualization of intraoperative surgery with 3D virtual reality models[22].
(b) Laparoscopic simulator with high-fidelity soft tissue representation[23].
(c) Mixed reality (MR) navigation system[24].

Other studies have also explored the use of MR in surgical and microsurgical simulation environments. In 2020, Galati et al. proposed a system based on Microsoft HoloLens, a Digital Imaging and Communication in Medicine (DICOM) viewer, and a visualization tool developed in Unity. This system improves the speed and precision of surgeries by displaying real-time information directly in the surgeon's visor, eliminating the need to leave the operating table. However, this approach presents challenges such as increased physical strain, discomfort due to the device's weight, and battery autonomy issues [25]. In 2023, Xiang et al. developed an MR framework for microsurgery simulation, combining a surgical microscope with real precision instruments, offering an immersive experience with visual and tactile interaction. This system enables the practice of anastomosis skills and uses vision-based tracking to monitor instruments and artificial blood vessels, as well as to quickly create virtual assets in various microsurgical specialties [26]. Also in 2023, Jain et al. explored the use of mixed reality (MR) technology in neurosurgical teaching, given the decline in cadaveric dissections and the need for new learning methods. Three neurosurgeons served as facilitators using the HoloLens 2 device without prior student training. Eight neurosurgery residents evaluated the experience, finding a short learning curve and rating the device as engaging, reliable, and easy to use. Although opinions were mixed on whether MR should replace traditional methods, the study demonstrates that this technology is viable for neurosurgical training [27]. These studies highlight the potential of MR to enhance both training and surgical outcomes, though technological challenges remain to be addressed.

Application in surgical innovation

MR is gaining traction in surgical education, with several companies heavily investing in this technology (Table 2). Microsoft, through its HoloLens project and Windows Mixed Reality, has developed an MR system that combines high-precision hardware and software.

This system has been used in medical, industrial, and educational applications, allowing surgeons to visualize three-dimensional holograms during surgical procedures without disrupting workflow. This technology improves precision and reduces errors; moreover, it is a pioneer in clinical studies and simulations[28]. Magic Leap, on the other hand, has developed light field technology that provides a better sense of fusion between the physical and virtual worlds, achieving greater realism in 3D image projection. This enables real-time medical collaboration and has enhanced training and diagnostics in surgical specialties [29,30].

Finally, MetaVision is bringing MR to the end user by commercializing a more affordable device, although it is geared toward the consumer market; this company has popularized MR and facilitated its adoption in medical education and clinical simulation[31].

Table 2. Main features of the leading MR devices.

Device	Main features	Price (USD)
HoloLens[28]	Transparent holographic lenses, 2-3 hours battery life in active use, Wi-Fi 802.11ac and Bluetooth 4.1 connectivity, 2MP cameras, 64GB storage.	3,000
Magic Leap One[28]	40° FOV, 1280 x 960 resolution per eye, rechargeable battery, Bluetooth 4.2 and Wi-Fi connectivity, 1080p RGB color camera, 64GB SSD storage.	2500
Meta 2[32]	90° field of view, 2.5K resolution, 9-foot cable for data and power, wired connectivity, 720p RGB camera, 128GB storage.	1500

In Mexico, the Universidad Nacional Autónoma de México (UNAM) successfully used an innovative lens system to visualize a hologram of the patient and performed the first surgery using MR. The experience gained has led to collaboration with Microsoft on a holographic surgery project involving specialists from 13 countries[33]. Additionally, in 2019, Arroyo-Berezowsky et al. conducted a study with 10 residents, where the VR group completed the task in 25.84 minutes, compared to 31.6 minutes for the control group, highlighting that the VR group tended to finish earlier[34]. On the other hand, in 2024, García et al. developed VirtualCPR, a virtual reality application for CPR training [35]. Finally, in 2016, Medellín-Castillo et al. presented a new 3D digital cephalometry approach with haptic support, which improved precision and reduced errors and variability compared to 2D and 2½D methods, proving to be more intuitive and efficient for dental surgeons [36].

In Brazil, in 2016, da Cruz et al. studied preoperative warm-up with virtual reality simulators and found a significant improvement in surgical performance among medical students with basic laparoscopy experience (37). Additionally, in 2016, de Faria et al. developed an interactive and stereoscopic resource for teaching neuroanatomy, significantly improving student learning compared to traditional teaching methods [38]. In Spain, researchers from the Universidad de Málaga demonstrated that virtual reality is a viable and more efficient alternative to 3D-printed models for classifying proximal humerus fractures in pre-surgical planning [39].

In Peru, the situation is different. Although the country has approximately 35 medical schools or faculties in 18 of its 24 provinces, only about 14% of them use virtual reality interfaces[40], and not all employ digital devices or have annual subscriptions for courses such as Physiology, Anatomy, Histology, Surgery, and/or Pathology [41-43]. This contrasts with other countries in the region and around the world that are promoting the use of augmented and virtual reality to improve educational processes [44,45]. While efforts are being made to incorporate new technologies in line with global developments, such as the use of surgical robots like Da Vinci [46], the current Peruvian context requires an accelerated renewal of medical education systems[47,48]. This should go beyond conventional educational objectives and include reforms ranging from the student admission process to organized educational quality.

The use of mixed reality (MR) in education in Peru is more common in Physics (15%), Computer Science, and Engineering (around 12%), while disciplines such as Astronomy, Geology, and Earth Sciences have much lower adoption rates (less than 2%). This suggests that technological and scientific areas benefit more from MR, while other fields are still lagging behind in its use (Figure 3).

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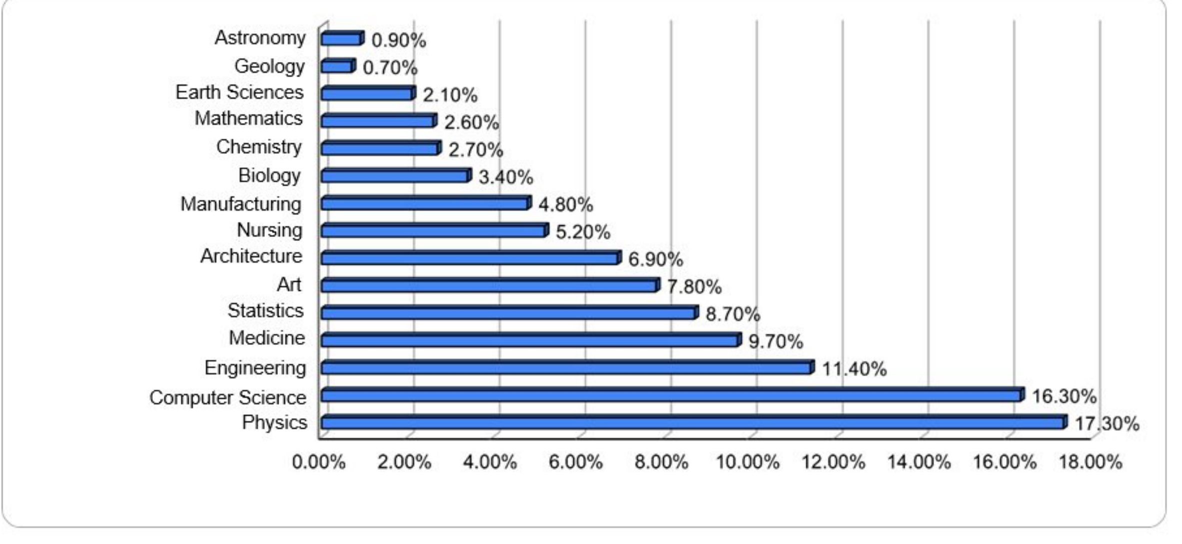

Figure 3. Current state of MR use in education in Peru[49].

CONCLUSION

To effectively implement these technologies in Latin America, several factors need to be considered: investment in infrastructure, healthcare personnel training, and adaptation to local needs[49]. MR has enormous potential to enhance both medical education and patient treatment[50], especially compared to Europe and North America, where significant increases in surgical efficiency have been observed. There is a weighted mean difference of 12.31 in skill training capacity [51], along with improvements in educational quality, as the average time of surgical procedures has been reduced to 97.62±35.59 minutes, compared to traditional cadaver-based teaching methods, which have an average time of 121.34±12.17 minutes[52,53]. Despite financial and infrastructural challenges, lessons learned from other regions can guide the successful integration of mixed reality into the Latin American medical field, adapting to its unique context [54-55]. (Figure 4).

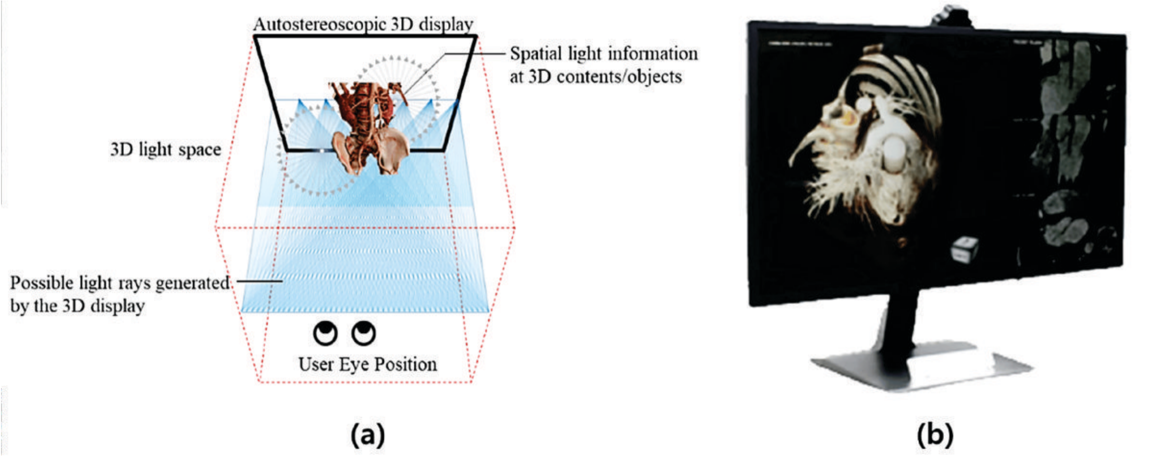

Figura 3. (a) Concept of 3D light field visualization based on eye-tracking, illustrating the generation and modeling of directional light rays.
(b) 3D visualization prototype for medical applications: 3D cardiac computed tomography navigator. Obtained under the CC BY 4.0 license[56].

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REFERENCES

1. McKnight RR, Pean CA, Buck JS, Hwang JS, Hsu JR, Pierrie SN. Virtual Reality and Augmented Reality—Translating Surgical Training into Surgical Technique. Curr Rev Musculoskelet Med. 2020;13(6):663–74. doi:10.1007/s12178-020-09667-3

2. Tepper OM, Rudy HL, Lefkowitz A, Weimer KA, Marks SM, Stern CS, et al. Mixed Reality with HoloLens: Where Virtual Reality Meets Augmented Reality in the Operating Room. Plast Reconstr Surg. 2017;140(5):1066. doi:10.1097/PRS.0000000000003802

3. Yoon JW, Chen RE, Kim EJ, Akinduro OO, Kerezoudis P, Han PK, et al. Augmented reality for the surgeon: Systematic review. Int J Med Robot. 2018;14(4):e1914. doi:10.1002/rcs.1914

4. Vervoorn MT, Wulfse M, Doormaal TPCV, Ruurda JP, Kaaij NPV der, Heer LMD. Mixed Reality in Modern Surgical and Interventional Practice: Narrative Review of the Literature. JMIR Serious Games. 2023;11(1):e41297. doi:10.2196/41297

5. Cornejo J, Cornejo-Aguilar JA, Vargas M, Helguero CG, Milanezi de Andrade R, Torres-Montoya S, et al. Anatomical Engineering and 3D Printing for Surgery and Medical Devices: International Review and Future Exponential Innovations. BioMed Res Int. 2022;2022(1):6797745. doi:10.1155/2022/6797745

6. Zhang J, Yu N, Wang B, Lv X. Trends in the Use of Augmented Reality, Virtual Reality, and Mixed Reality in Surgical Research: a Global Bibliometric and Visualized Analysis. Indian J Surg. 2022;84(1):52–69. doi:10.1007/s12262-021-03243-w

7. Carmigniani J, Furht B. Augmented Reality: An Overview. En: Furht B, editor. Handbook of Augmented Reality [Internet]. New York, NY: Springer; 2011 [citado el 29 de agosto de 2024]. p. 3–46. doi:10.1007/978-1-4614-0064-6_1

8. Allcca D, Nacarino A, Sanchez B, Castro R, La-Rosa A, Cornejo J, et al. Mechatronics Bio-Design of Hip Prosthesis using Mechanic of Materials Analysis and Finite Element Method: A Proof of Concept. En: 2024 5th International Conference on Recent Trends in Computer Science and Technology (ICRTCST) [Internet]. 2024 [citado el 31 de agosto de 2024]. p. 438–43. doi:10.1109/ICRTCST61793.2024.10578526

9. Coutrix C, Nigay L. Mixed reality: a model of mixed interaction. En: Proceedings of the working conference on Advanced visual interfaces [Internet]. New York, NY, USA: Association for Computing Machinery; 2006 [citado el 29 de agosto de 2024]. p. 43–50. (AVI '06). doi:10.1145/1133265.1133274

10. Liao T. Future directions for mobile augmented reality research: Understanding relationships between augmented reality users, nonusers, content, devices, and industry. Mob Media Commun. 2019;7(1):131–49. doi:10.1177/2050157918792438

11. Rokhsaritalemi S, Sadeghi-Niaraki A, Choi S-M. A Review on Mixed Reality: Current Trends, Challenges and Prospects. Appl Sci. 2020;10(2):636. doi:10.3390/app10020636

12. Carmigniani J, Furht B, Anisetti M, Ceravolo P, Damiani E, Ivkovic M. Augmented reality technologies, systems and applications. Multimed Tools Appl. 2011;51(1):341–77. doi:10.1007/s11042-010-0660-6

13. Moser T, Hohlagschwandtner M, Kormann-Hainzl G, Pölzlbauer S, Wolfartsberger J. Mixed Reality Applications in Industry: Challenges and Research Areas. En: Winkler D, Biffl S, Bergsmann J, editores. Software Quality: The Complexity and Challenges of Software Engineering and Software Quality in the Cloud. Cham: Springer International Publishing; 2019. p. 95–105. doi:10.1007/978-3-030-05767-1_7

14. Adams L, Krybus W, Meyer-Ebrecht D, Rueger R, Gilsbach JM, Moesges R, et al. Computer-assisted surgery. IEEE Comput Graph Appl. 1990;10(3):43–51. doi:10.1109/38.55152

15. Cornejo J, Cornejo J, Vargas M, Carvajal M, Perales P, Rodríguez G, et al. SY-MIS Project: Biomedical Design of Endo-Robotic and Laparoscopic Training System for Surgery on the Earth and Space. Emerg Sci J. 2024;8(2):372–93. doi:10.28991/ESJ-2024-08-02-01

16. Cornejo J, Cornejo-Aguilar JA, Gonzalez C, Sebastian R. Mechanical and Kinematic Design of Surgical Mini Robotic Manipulator used into SP-LAP Multi-DOF Platform for Training and Simulation. En: 2021 IEEE XXVIII International Conference on Electronics, Electrical Engineering and Computing (INTERCON) [Internet]. 2021 [citado el 31 de agosto de 2024]. p. 1–4. doi:10.1109/INTERCON52678.2021.9532965

17. Cornejo J, Barrera S, Ruiz CAH, Gutierrez F, Casasnovas MO, Kot L, et al. Industrial, Collaborative and Mobile Robotics in Latin America: Review of Mechatronic Technologies for Advanced Automation. Emerg Sci J. 2023;7(4):1430–58. doi:10.28991/ESJ-2023-07-04-025

18. Dagnino G, Kundrat D. Robot-assistive minimally invasive surgery: trends and future directions. Int J Intell Robot Appl [Internet]. 2024 [citado el 7 de octubre de 2024]; doi:10.1007/s41315-024-00341-2

19. Cornejo J, Cornejo-Aguilar JA, Sebastian R, Perales P, Gonzalez C, Vargas M, et al. Mechanical Design of a Novel Surgical Laparoscopic Simulator for Telemedicine Assistance and Physician Training during Aerospace Applications. En: 2021 IEEE 3rd Eurasia Conference on Biomedical Engineering, Healthcare and Sustainability (ECBIOS) [Internet]. 2021 [citado el 31 de agosto de 2024]. p. 53–6. doi:10.1109/ECBIOS51820.2021.9510753

20. Cornejo J, Perales-Villarroel JP, Sebastian R, Cornejo-Aguilar JA. Conceptual Design of Space Biosurgeon for Robotic Surgery and Aerospace Medicine. En: 2020 IEEE ANDESCON [Internet]. 2020 [citado el 31 de agosto de 2024]. p. 1–6. doi:10.1109/ANDESCON50619.2020.9272122

21. De Mauro A, Raczkowsky J, Halatsch ME, Wörn H. Mixed Reality Neurosurgical Microscope for Training and Intra-operative Purposes. En: Shumaker R, editor. Virtual and Mixed Reality [Internet]. Berlin, Heidelberg: Springer Berlin Heidelberg; 2009 [citado el 20 de agosto de 2024]. p. 542–9. (Lecture Notes in Computer Science; vol. 5622). doi:10.1007/978-3-642-02771-0_60

22. Ujiie H, Chiba R, Yamaguchi A, Nomura S, Shiiya H, Fujiwara-Kuroda A, et al. Developing a Virtual Reality Simulation System for Preoperative Planning of Robotic-Assisted Thoracic Surgery. J Clin Med. 2024;13(2):611. doi:10.3390/jcm13020611

23. Deng Z, Xiang N, Pan J. State of the Art in Immersive Interactive Technologies for Surgery Simulation: A Review and Prospective. Bioengineering. 2023;10(12):1346. doi:10.3390/bioengineering10121346

24. Lin Z, Lei C, Yang L. Modern Image-Guided Surgery: A Narrative Review of Medical Image Processing and Visualization. Sensors. 2023;23(24):9872. doi:10.3390/s23249872

25. Galati R, Simone M, Barile G, De Luca R, Cartanese C, Grassi G. Experimental Setup Employed in the Operating Room Based on Virtual and Mixed Reality: Analysis of Pros and Cons in Open Abdomen Surgery. J Healthc Eng. 2020;2020(1):8851964. doi:10.1155/2020/8851964

26. Xiang N, Liang H-N, Yu L, Yang X, Zhang JJ. A mixed reality framework for microsurgery simulation with visual-tactile perception. Vis Comput. 2023;39(8):3661–73. doi:10.1007/s00371-023-02964-1

27. Jain S, Timofeev I, Kirollos RW, Helmy A. Use of Mixed Reality in Neurosurgery Training: A Single Centre Experience. World Neurosurg. 2023;176:e68–76. doi:10.1016/j.wneu.2023.04.107

28. Palumbo A. Microsoft HoloLens 2 in Medical and Healthcare Context: State of the Art and Future Prospects. Sensors. 2022;22(20). doi:10.3390/s22207709

29. Cornejo J, Cornejo-Aguilar JA, Palomares R. Biomedik Surgeon: Surgical Robotic System for Training and Simulation by Medical Students in Peru. En: 2019 International Conference on Control of Dynamical and Aerospace Systems (XPOTRON) [Internet]. 2019 [citado el 31 de agosto de 2024]. p. 1–4. doi:10.1109/XPOTRON.2019.8705717

30. Zari G, Condino S, Cutolo F, Ferrari V. Magic Leap 1 versus Microsoft HoloLens 2 for the Visualization of 3D Content Obtained from Radiological Images. Sensors. 2023;23(6):3040. doi:10.3390/s23063040

31. Westermeier F, Brübach L, Wienrich C, Latoschik ME. Assessing Depth Perception in VR and Video See-Through AR: A Comparison on Distance Judgment, Performance, and Preference. IEEE Trans Vis Comput Graph. 2024;30(5):2140–50. doi:10.1109/TVCG.2024.3372061

32. Anaya-Sánchez R, Rejón-Guardia F, Molinillo S. Impact of virtual reality experiences on destination image and visit intentions: the moderating effects of immersion, destination familiarity and sickness. Int J Contemp Hosp Manag [Internet]. 2024 [citado el 31 de agosto de 2024];ahead-of-print(ahead-of-print). doi:10.1108/IJCHM-09-2023-1488

33. Zaragoza Pérez R, Cuevas Escudero AL. Realidad aumentada en la enseñanza. RDU UNAM [Internet]. 2020 [citado el 31 de agosto de 2024]; doi:10.22201/cuaieed.16076079e.2020.21.6.9

34. Arroyo-Berezowsky C, Jorba-Elguero P, Altamirano-Cruz MA, Quinzaños-Fresnedo J. Usefulness of immersive virtual reality simulation during femoral nail application in an orthopedic fracture skills course. J Musculoskelet Surg Res. 2019;3:326. doi:10.4103/jmsr.jmsr_78_19

35. De Jesus Encarnacion Ramirez M, Chmutin G, Nurmukhametov R, Soto GR, Kannan S, Piavchenko G, et al. Integrating Augmented Reality in Spine Surgery: Redefining Precision with New Technologies. Brain Sci. 2024;14(7):645. doi:10.3390/brainsci14070645

36. Medellín-Castillo HI, Govea-Valladares EH, Pérez-Guerrero CN, Gil-Valladares J, Lim T, Ritchie JM. The evaluation of a novel haptic-enabled virtual reality approach for computer-aided cephalometry. Comput Methods Programs Biomed. 2016;130:46–53. doi:10.1016/j.cmpb.2016.03.014

37. da Cruz JAS, dos Reis ST, Cunha Frati RM, Duarte RJ, Nguyen H, Srougi M, et al. Does Warm-Up Training in a Virtual Reality Simulator Improve Surgical Performance? A Prospective Randomized Analysis. J Surg Educ. 2016;73(6):974–8. doi:10.1016/j.jsurg.2016.04.020

38. de Faria JWV, Teixeira MJ, de Moura Sousa Júnior L, Otoch JP, Figueiredo EG. Virtual and stereoscopic anatomy: when virtual reality meets medical education. J Neurosurg. 2016;125(5):1105–11. doi:10.3171/2015.8.JNS141563

39. Almirón Santa-Bárbara R, García Rivera F, Lamb M, Víquez Da-Silva R, Gutiérrez Bedmar M. New technologies for the classification of proximal humeral fractures: Comparison between Virtual Reality and 3D printed models—a randomised controlled trial. Virtual Real. 2023;27(3):1623–34. doi:10.1007/s10055-023-00757-4

40. Morales-Mere J, Chessa JJ, Palomares R, Cornejo J. Mixed Reality System for Education and Innovation in Prehospital Interventions at Peruvian Fire Department. En: 2020 IEEE XXVII International Conference on Electronics, Electrical Engineering and Computing (INTERCON) [Internet]. 2020 [citado el 1 de septiembre de 2024]. p. 1–4. doi:10.1109/INTERCON50315.2020.9220259

41. Wilson AB, Miller CH, Klein BA, Taylor MA, Goodwin M, Boyle EK, et al. A meta-analysis of anatomy laboratory pedagogies. Clin Anat. 2018;31(1):122–33. doi:10.1002/ca.22934

42. Cornejo-Aguilar JA, Cornejo J, Vargas M, Sebastian R. The revolution of robotic surgery in latin america and the future implementation in the healthcare system of Peru: La revolución de la cirugía robótica en latino américa y la futura implementación en el sistema de salud del perú. Rev Fac Med Humana. 2019;19(1):5. doi:10.25176/RFMH.v19.n1.1800

43.Cornejo J, Cornejo Aguilar JA, Perales Villarroel JP. INTERNATIONAL INNOVATIONS IN MEDICAL ROBOTICS TO IMPROVE THE PATIENT MANAGEMENT IN PERU: INNOVACIONES INTERNACIONALES EN ROBÓTICA MÉDICA PARA MEJORAR EL MANEJO DEL PACIENTE EN PERÚ. Rev Fac Med Humana. 2019;19(4):1. doi:10.25176/RFMH.v19i4.2349

44. Mendoza GAA, Lewis F, Plante P, Brassard C. Estado del arte sobre el uso de la realidad virtual, la realidad augmentada y el video 360° en educación superior. Edutec Rev Electrónica Tecnol Educ. 2023;(84):35–51. doi:10.21556/edutec.2023.84.2769

45. Cornejo J, Vargas M, Cornejo-Aguilar JA. Robotics and Biomedical Innovative Applications in Public Health during the COVID-19 Pandemic: Aplicaciones Innovadoras De La Robótica Y Biomédica En La Salud Pública Durante La Pandemia Del COVID-19. Rev Fac Med Humana [Internet]. 2020 [citado el 2 de septiembre de 2024];20(4). doi:10.25176/RFMH.v20i4.3042

46. Clínica Internacional adquiere el primer robot quirúrgico en el Perú | empresas | breca | cirugías | medicina | cirujanos | Intuitive Surgical | ECONOMIA | GESTIÓN [Internet]. [citado el 7 de octubre de 2024]. Disponible en: https://gestion.pe/economia/empresas/clinica-internacional-adquiere-el-primer-robot-quirurgico-en-el-peru-empresas-breca-cirugias-medicina-cirujanos-intuitive-surgical-noticia/#google_vignette

47. Vargas M, Cornejo J, De La Cruz-Vargas JA. Health without Borders: INICIB-URP leading Medical Education through Bioengineering and Mechatronic Technologies: Salud sin Fronteras: INICIB-URP liderando la Educación Médica a través de Bioingeniería y Tecnologías Mecatrónicas. Rev Fac Med Humana. 2024;24(3):07–11. doi:10.25176/RFMH.v24i3.6701

48. Vargas M, Cornejo J, Correa-López LE. Ingeniería biomédica: la revolución tecnológica para el futuro del sistema de salud peruano. Rev Fac Med Humana [Internet]. 2017 [citado el 2 de septiembre de 2024];16(2). doi:10.25176/RFMH.v16.n3.659

49. Caballero-Garriazo JA, Rojas-Huacanca JR, Sánchez-Castro A, Lázaro-Aguirre AF. Systematic review on the application of Virtual Reality in University Education. Rev Electrónica Educ. 2023;27(3):1–18. doi:10.15359/ree.27-3.17271

50. Morimoto T, Kobayashi T, Hirata H, Otani K, Sugimoto M, Tsukamoto M, et al. XR (Extended Reality: Virtual Reality, Augmented Reality, Mixed Reality) Technology in Spine Medicine: Status Quo and Quo Vadis. J Clin Med. 2022;11(2):470. doi:10.3390/jcm11020470

51. Zhang R, Jin X, Liu M, Tong HY. The Effectiveness of Augmented Reality/Mixed Reality in Medical Education: A Meta- Analysis [Internet]. 2024 [citado el 30 de agosto de 2024]. doi:10.21203/rs.3.rs-4549366/v1

52. Wu Q, Wang Y, Lu L, Chen Y, Long H, Wang J. Virtual Simulation in Undergraduate Medical Education: A Scoping Review of Recent Practice. Front Med [Internet]. 2022 [citado el 30 de agosto de 2024];9. doi:10.3389/fmed.2022.855403

53. Sadek O, Baldwin F, Gray R, Khayyat N, Fotis T. Impact of Virtual and Augmented Reality on Quality of Medical Education During the COVID-19 Pandemic: A Systematic Review. J Grad Med Educ. 2023;15(3):328–38. doi:10.4300/JGME-D-22-00594.1

54.Martel Cervantes C, Sandoval C, Palomares R, Borja Arroyo J, Murillo Manrique M, Cornejo J. BIOMEDICAL ANTHROPOMETRIC EVALUATION AND CONCEPTUAL MECHANICAL DESIGN OF A ROBOTIC SYSTEM FOR LOWER LIMBS PASSIVE-REHABILITATION ON POST-STROKE PATIENTS. Revista de la Facultad de Medicina Humana. 2024 Apr 1;24(2). doi: 10.25176/rfmh.v24i2.6550

55.Sandoval C, Martel C, Palomares R, Arroyo JB, Manrique MFM, Cornejo J. Conceptual mechatronic design of ankle-foot exoskeleton system for assisted rehabilitation of pediatric patients with spastic cerebral palsy. In: 2023 IEEE MIT Undergraduate Research Technology Conference (URTC). IEEE; 2023. doi: 10.1109/URTC60662.2023.10534922

56.Kang D, Choi JH, Hwang H. Autostereoscopic 3D display system for 3D medical images. Applied Sciences. 2022 Apr 24;12(9):4288. doi: 10.3390/app1209428