Augmented Reality in Orthopedic Surgery

Subjects: Orthopedics
Contributor: Stefano Marco Paolo Rossi, Fabio Mancino, Ludovico Lucenti, Francesco Benazzo

The development of augmented reality (AR) and its application in total joint arthroplasty aims at improving the accuracy and precision in implant components' positioning, hopefully leading to increased outcomes and survivorship.

Keywords: augmented reality ; total joint arthroplasty ; total knee arthroplasty ; hip arthroplasty ; accuracy ; survivorship ; clinical outcomes

1. Introduction

The development of new technologies in total joint arthroplasty (TJA) has gained increasing interest in the last two decades. Since the introduction of minimally invasive surgery (MIS), computer-assisted orthopaedic surgery (CAOS), and robotic surgery, computer navigation has become a powerful tool for the correct positioning of the implant components [1][2][3]. Conventionally, surgical imaging can be classified as off-line, taken before and after surgery (X-rays, computed tomography [CT], magnetic resonance imaging [MRI]), and on-line (intraoperative X-ray fluoroscopy, ultrasound [US]) [4][5]. On-line 2-dimensional (2D) intraoperative imaging can be supportive to enhance accuracy in TJA; however, despite the advantages, it is associated with several major problems including the necessity for video monitors, the interpretation and conversion of the 2D images into 3-dimensional (3D) images, the potential overlapping of anatomic structures, and increased radiation exposure [6].

The concept of augmented reality (AR) was introduced by Azuma et al. [7] as a variation of virtual reality (VR). The difference is that AR allows the user to see the real world with virtual objects superimposed upon it, supplementing the reality with virtual computer-generated sensory impressions, enhancing the user's ability to visualize a patient's anatomy.

2. General Principles of Augmented Reality

The most common type of AR technology is based on the superimposition of a computer-generated image in the real world that is captured with a camera and then projected through screens [8][9][10][11][12][13][14][15]. Special head-mounted displays (HMD) or "smart glasses" have been successfully used to obtain a view of the surgical site without the need for any screens [8][16] that force the surgeon to look away from the surgical site, as usually happens with standard 2D intraoperative imaging.

A position tracking system, a display device, and a system control software are the basic elements required [17]. The first step is the registration phase which can be marker-based [18], marker-less (surface registration) [19], or through an augmented C-arm device [20]. The surface registration was introduced by Liebmann et al. [19] as a radiation-free approach with intraoperative surface digitization and navigation. Following this, the tracking phase allows the object to remain in the correct position during the surgical procedure, despite eventual motion, and adapt in a 3D space to the user and the instruments' position. Therefore, a correct registration phase is essential for the success of the following phases [19]. After the registration and tracking are performed, the elaborated images are shown through three different approaches: HMD, monitors, and projectors [7]. Among those, video see-through headsets (HMD) have been introduced to avoid the necessity for a display; however, they are not free from complications including headaches and nausea being reported by users [21][22]. Alternatively, the virtual information can be directly projected onto the real environment, overlaying the information on a semi-transparent mirror [23].

3. Applications and Influences

The application of AR in modern orthopaedic surgery and TJA is progressively finding wider approval with promising results in multiple settings. Indeed, it has been widely used in spine surgery, considering the complexity of the anatomical district and the risk of iatrogenic injury during instrumentation [19][24][25][26][27][28][29][30]; favorable outcomes have also been reported in complex corrective osteotomies and trauma surgery, increasing accuracy while reducing radiation exposure and surgery time [30][31][32].

The correct implantation of prosthetic components in TJA is a key element for success in terms of functional outcomes, patient recovery and rehabilitation, and implant survivorship [33]. For those reasons, different technological innovations have been developed and introduced including robotic surgery [34], 3-D printed patient-specific instrumentation (PSI) [35], navigation devices [3], and, finally, AR [36]. To date, there are several different AR systems that have been applied in preclinical and clinical studies [37][38][39][40][41][42][43][44][45][46][47][48]; however, their application in TJA has not been thoroughly investigated yet. Despite that, a few studies have reported the potential benefits of this technology in terms of the reduced radiation exposure of patients and OR staff, reduced surgical time, and improved accuracy of surgical performance. In addition, studies have reported that, at least in Sawbones, AR navigation provides more accurate results in terms of implant positioning when compared to the conventional free-hand technique in total hip [18][22][23][41][42][49][50] and knee [37][38][39][40] arthroplasty.

Regarding the application in THA, according to the current literature, researchers can state that AR is able to provide several advantages, particularly with regards to increased accuracy in acetabular component positioning. Alexander et al. [43] compared an AR system with standard fluoroscopic guidance on pelvic sawbones reporting increased accuracy of the placement angles. Despite that, the study is limited by its application to sawbones, and clinically relevant differences with conventional techniques have not yet been reported to support this technique in daily practice. Similarly, Ogawa et al. [18] [42] reported promising results when an AR system was used to improve the quality of the cup positioning considering that the conventional tools may not recognize determinant elements such as the pelvic tilt or the pelvic movement related to the retractors, leading to potential version errors. In spite of that, even though there was an absence of reported complications, there was no evaluation of the clinical outcomes, forcing researchers to suggest that additional studies are necessary to assess the cost-effectiveness and risk-effectiveness of the technique before its introduction in daily practice. This technology has also been explored in HR by Liu et al. [22] to evaluate the accuracy of the guide hole along the axis of the femoral neck in a sawbones model. The authors reported an error of 2 mm and 2° for position and direction compared to what was planned, providing good accuracy according to the Audenaert et al. criteria [51]. Nevertheless, despite the promising results, the biggest obstacle to its application in a realistic setting would be to identify suitable image processing algorithms to segment the target from the surrounding surgical scene in order to correctly register it, limiting its dissemination to date.

Similar results have been described in TKA surgery. Tsukada et al. [40], reported on the AR-KNEE system and suggested that it may provide reliable accuracy for the coronal, sagittal, and rotational alignment when used for tibial and femoral resection and that it may become a useful alternative to conventional navigation devices. In addition, the authors reported promising results in an experimental setting when analyzing the error in distal femoral resection (<1.0°) in both the coronal and sagittal planes. Their non-randomized comparative study showed that the AR system can provide significantly greater accuracy during distal femoral resection in TKA compared with the conventional intramedullary guide. Similarly, Fallavollita et al. [37], after the promising results obtained at the preclinical level, aimed to extend their study to a clinical level to assess the technical efficacy of this AR technique. Indeed, it has the potential to quickly simplify the workflow of mechanical axis deviation measurement, by combining X-ray and video images into a single procedure while avoiding the exposure to ionizing radiation of patients and operators. However, considering the lack of available literature in clinical settings, further high-quality studies are probably necessary before researchers widely support the diffusion and application of AR systems in TKA.

Interesting results have also been reported regarding RSA and TEA, even though these fields are yet to be fully explored and thoroughly understood. In particular, baseplate glenoid component positioning has been studied by several authors [46][47][48] in sawbones and cadaveric scapulae specimens to evaluate the potential benefits of AR technology, and these studies reported that baseplate navigation in RSA using AR through an HMD seems feasible, showing high accuracy and precision at the preclinical level. However, the application of this novel technology in such fields is still in its infancy and various technical problems still need to be addressed before it can be widely used in clinical practice.

Similarly, Tanji et al. [45] investigated the field of TEA stating that the AR technique can provide several advantages over the conventional surgical technique, with quick registration and easy application while being able to reproduce the preoperative placement plan onto the surgical field, potentially leading to more accurate component placement. Nevertheless, researchers still need valuable data to confirm these promising preliminary results in order to support the application of this technology in the clinical setting of TEA.

In spite of the promising preliminary results, researchers must remember that, recently, many surgical techniques have been introduced hoping to achieve improved results in total joint arthroplasty including MIS, PSI, CAOS, and, lastly, robotics. However, after initial interest, they can easily follow Scott's description of the parabola of the rise and fall of surgical techniques [52], facing an exponential drop-off when the high costs of such innovative tools are not balanced by improved clinical outcomes.

References

1. Cheng, T.; Feng, J.G.; Liu, T.; Zhang, X.L. Minimally invasive total hip arthroplasty: A systematic review. Int. Orthop. 2009, 33, 1473–1481.
2. Mancino, F.; Cacciola, G.; Malahias, M.-A.; De Filippis, R.; De Marco, D.; Di Matteo, V.; Gu, A.; Sculco, P.K.; Maccauro, G.; De Martino, I. What are the benefits of robotic-assisted total knee arthroplasty over conventional manual total knee arthroplasty? A systematic review of comparative studies. Orthop. Rev. 2020, 12, 8657.
3. Jones, C.W.; Jerabek, S.A. Current Role of Computer Navigation in Total Knee Arthroplasty. J. Arthroplast. 2018, 33, 1989–1993.
4. Nikou, C.; Digioia, A.M.; Blackwell, M.; Jaramaz, B.; Kanade, T. Augmented reality imaging technology for orthopaedic surgery. Oper. Tech. Orthop. 2000, 10, 82–86.
5. Chen, T.K.; Abolmaesumi, P.; Pichora, D.R.; Ellis, R.E. A system for ultrasound-guided computer-assisted orthopaedic surgery. Comput. Aided Surg. 2005, 10, 281–292.
6. Tonetti, J.; Boudissa, M.; Kerschbaumer, G.; Seurat, O. Role of 3D intraoperative imaging in orthopedic and trauma surgery. Orthop. Traumatol. Surg. Res. 2019, 106, S19–S25.
7. Azuma, R.T. A Survey of Augmented Reality. Presence Teleoperators Virtual Environ. 1997, 6, 355–385.
8. Tabrizi, L.B.; Mahvash, M. Augmented reality–guided neurosurgery: Accuracy and intraoperative application of an image projection technique. J. Neurosurg. 2015, 123, 206–211.
9. Vavra, P.; Roman, J.; Zonča, P.; Ihnát, P.; Němec, M.; Kumar, J.; Habib, N.; El-Gendi, A. Recent Development of Augmented Reality in Surgery: A Review. J. Heal. Eng. 2017, 2017, 4574172.
10. Sugimoto, M.; Yasuda, H.; Koda, K.; Suzuki, M.; Yamazaki, M.; Tezuka, T.; Kosugi, C.; Higuchi, R.; Watayo, Y.; Yagawa, Y.; et al. Image overlay navigation by markerless surface registration in gastrointestinal, hepatobiliary and pancreatic surgery. J. Hepato-Biliary-Pancreat. Sci. 2009, 17, 629–636.
11. Gavaghan, K.A.; Peterhans, M.; Oliveira-Santos, T.; Weber, S. A Portable Image Overlay Projection Device for Computer-Aided Open Liver Surgery. IEEE Trans. Biomed. Eng. 2011, 58, 1855–1864.
12. Gavaghan, K.; Oliveira-Santos, T.; Peterhans, M.; Reyes, M.; Kim, H.; Anderegg, S.; Weber, S. Evaluation of a portable image overlay projector for the visualisation of surgical navigation data: Phantom studies. Int. J. Comput. Assist. Radiol. Surg. 2011, 7, 547–556.
13. Wen, R.; Chui, C.-K.; Ong, S.-H.; Lim, K.-B.; Chang, S.K.-Y. Projection-based visual guidance for robot-aided RF needle insertion. Int. J. Comput. Assist. Radiol. Surg. 2013, 8, 1015–1025.
14. Kocev, B.; Ritter, F.; Linsen, L. Projector-based surgeon–computer interaction on deformable surfaces. Int. J. Comput. Assist. Radiol. Surg. 2013, 9, 301–312.
15. Pessaux, P.; Diana, M.; Soler, L.; Piardi, T.; Mutter, D.; Marescaux, J. Towards cybernetic surgery: Robotic and augmented reality-assisted liver segmentectomy. Langenbeck's Arch. Surg. 2014, 400, 381–385.
16. Badiali, G.; Ferrari, V.; Cutolo, F.; Freschi, C.; Caramella, D.; Bianchi, A.; Marchetti, C. Augmented reality as an aid in maxillofacial surgery: Validation of a wearable system allowing maxillary repositioning. J. Cranio-Maxillofac. Surg. 2014, 42, 1970–1976.
17. Blackwell, M.; Morgan, F.; DiGioia, A.M., III. Augmented Reality and Its Future in Orthopaedics. Clin. Orthop. Relat. Res. 1998, 354, 111–122.
18. Ogawa, H.; Hasegawa, S.; Tsukada, S.; Matsubara, M. A Pilot Study of Augmented Reality Technology Applied to the Acetabular Cup Placement During Total Hip Arthroplasty. J. Arthroplast. 2018, 33, 1833–1837.
19. Liebmann, F.; Roner, S.; von Atzigen, M.; Scaramuzza, D.; Sutter, R.; Snedeker, J.; Farshad, M.; Fürnstahl, P. Pedicle screw navigation using surface digitization on the Microsoft HoloLens. Int. J. Comput. Assist. Radiol. Surg. 2019, 14, 1157–1165.

20. Navab, N.; Heining, S.-M.; Traub, J. Camera Augmented Mobile C-Arm (CAMC): Calibration, Accuracy Study, and Clinical Applications. IEEE Trans. Med. Imaging 2009, 29, 1412–1423.

21. Shuhaiber, J.H. Augmented Reality in Surgery. Arch. Surg. 2004, 139, 170–174.

22. Liu, H.; Auvinet, E.; Giles, J.; Baena, F.R.Y. Augmented Reality Based Navigation for Computer Assisted Hip Resurfacing: A Proof of Concept Study. Ann. Biomed. Eng. 2018, 46, 1595–1605.

23. Van Krevelen, D.; Poelman, R. A survey of augmented reality technologies, applications and limitations. Int. J. Virtual Real. 2010, 9, 1–20.

24. Molina, C.A.; Theodore, N.; Ahmed, A.K.; Westbroek, E.M.; Mirovsky, Y.; Harel, R.; Orru', E.; Khan, M.; Witham, T.; Sciubba, D.M. Augmented reality–assisted pedicle screw insertion: A cadaveric proof-of-concept study. J. Neurosurg. Spine 2019, 31, 139–146.

25. Gibby, J.T.; Swenson, S.A.; Cvetko, S.; Rao, R.; Javan, R. Head-mounted display augmented reality to guide pedicle screw placement utilizing computed tomography. Int. J. Comput. Assist. Radiol. Surg. 2018, 14, 525–535.

26. Elmi-Terander, A.; Burström, G.; Nachabe, R.; Skulason, H.; Pedersen, K.; Fagerlund, M.; Ståhl, F.; Charalampidis, A.; Söderman, M.; Holmin, S.; et al. Pedicle Screw Placement Using Augmented Reality Surgical Navigation with Intraoperative 3D Imaging. Spine 2019, 44, 517–525.

27. Müller, F.; Roner, S.; Liebmann, F.; Spirig, J.M.; Fürnstahl, P.; Farshad, M. Augmented reality navigation for spinal pedicle screw instrumentation using intraoperative 3D imaging. Spine J. 2020, 20, 621–628.

28. Yoon, J.W.; Chen, R.E.; Han, P.K.; Si, P.; Freeman, M.W.D.; Pirris, S.M. Technical feasibility and safety of an intraoperative head-up display device during spine instrumentation. Int. J. Med. Robot. Comput. Assist. Surg. 2016, 13, e1770.

29. Wu, J.-R.; Wang, M.-L.; Liu, K.-C.; Hu, M.-H.; Lee, P.-Y. Real-time advanced spinal surgery via visible patient model and augmented reality system. Comput. Methods Programs Biomed. 2014, 113, 869–881.

30. Kosterhon, M.; Gutenberg, A.; Kantelhardt, S.R.; Archavlis, E.; Giese, A. Navigation and Image Injection for Control of Bone Removal and Osteotomy Planes in Spine Surgery. Oper. Neurosurg. 2017, 13, 297–304.

31. Ortega, G.; Wolff, A.; Baumgaertner, M.; Kendoff, D. Usefulness of a head mounted monitor device for viewing intraoperative fluoroscopy during orthopaedic procedures. Arch. Orthop. Trauma. Surg. 2007, 128, 1123–1126.

32. Shen, F.; Chen, B.; Guo, Q.; Qi, Y.; Shen, Y. Augmented reality patient-specific reconstruction plate design for pelvic and acetabular fracture surgery. Int. J. Comput. Assist. Radiol. Surg. 2012, 8, 169–179.

33. Mancino, F.; Cacciola, G.; Di Matteo, V.; Perna, A.; Proietti, L.; Greenberg, A.; Malahias, M.; Sculco, P.K.; Maccauro, G.; De Martino, I. Surgical implications of the hip-spine relationship in total hip arthroplasty. Orthop. Rev. 2020, 12, 8656.

34. Kayani, B.; Konan, S.; Tahmassebi, J.; Pietrzak, J.R.T.; Haddad, F.S. Robotic-arm assisted total knee arthroplasty is associated with improved early functional recovery and reduced time to hospital discharge compared with conventional jig-based total knee arthroplasty. Bone Jt. J. 2018, 100-B, 930–937.

35. Hafez, M.A.; Moholkar, K. Patient-specific instruments: Advantages and pitfalls. SICOT-J. 2017, 3, 66.

36. Makhni, E.C.; Makhni, S.; Ramkumar, P.N. Artificial Intelligence for the Orthopaedic Surgeon: An Overview of Potential Benefits, Limitations, and Clinical Applications. J. Am. Acad. Orthop. Surg. 2020, 29, 235–243.

37. Fallavollita, P.; Brand, A.; Wang, L.; Euler, E.; Thaller, P.; Navab, N.; Weidert, S. An augmented reality C-arm for intraoperative assessment of the mechanical axis: A preclinical study. Int. J. Comput. Assist. Radiol. Surg. 2016, 11, 2111–2117.

38. Tsukada, S.; Ogawa, H.; Nishino, M.; Kurosaka, K.; Hirasawa, N. Augmented reality-based navigation system applied to tibial bone resection in total knee arthroplasty. J. Exp. Orthop. 2019, 6, 1–7.

39. Iacono, V.; Farinelli, L.; Natali, S.; Piovan, G.; Screpis, D.; Gigante, A.; Zorzi, C. The use of augmented reality for limb and component alignment in total knee arthroplasty: Systematic review of the literature and clinical pilot study. J. Exp. Orthop. 2021, 8, 52.

40. Tsukada, S.; Ogawa, H.; Nishino, M.; Kurosaka, K.; Hirasawa, N. Augmented Reality-Assisted Femoral Bone Resection in Total Knee Arthroplasty. JBJS Open Access 2021, 6, e21.00001.

41. Fotouhi, J.; Alexander, C.P.; Unberath, M.; Taylor, G.; Lee, S.C.; Fuerst, B.; Johnson, A.; Osgood, G.; Taylor, R.H.; Khanuja, H.; et al. Plan in 2-D, execute in 3-D: An augmented reality solution for cup placement in total hip arthroplasty. J. Med. Imaging 2018, 5, 021205.

42. Ogawa, H.; Kurosaka, K.; Sato, A.; Hirasawa, N.; Matsubara, M.; Tsukada, S. Does An Augmented Reality-based Portable Navigation System Improve the Accuracy of Acetabular Component Orientation During THA? A Randomized

Controlled Trial. Clin. Orthop. Relat. Res. 2020, 478, 935–943.

43. Alexander, C.; Loeb, A.E.; Fotouhi, J.; Navab, N.; Armand, M.; Khanuja, H.S. Augmented Reality for Acetabular Component Placement in Direct Anterior Total Hip Arthroplasty. J. Arthroplast. 2020, 35, 1636–1641.e3.
44. Logishetty, K.; Western, L.; Morgan, R.; Iranpour, F.; Cobb, J.; Auvinet, E. Can an Augmented Reality Headset Improve Accuracy of Acetabular Cup Orientation in Simulated THA? A Randomized Trial. Clin. Orthop. Relat. Res. 2018, 477, 1190–1199.
45. Tanji, A.; Nagura, T.; Iwamoto, T.; Matsumura, N.; Nakamura, M.; Matsumoto, M.; Sato, K. Total elbow arthroplasty using an augmented reality–assisted surgical technique. J. Shoulder Elb. Surg. 2021, 31, 175–184.
46. Schlueter-Brust, K.; Henckel, J.; Katinakis, F.; Buken, C.; Opt-Eynde, J.; Pofahl, T.; Baena, F.R.Y.; Tatti, F. Augmented-Reality-Assisted K-Wire Placement for Glenoid Component Positioning in Reversed Shoulder Arthroplasty: A Proof-of-Concept Study. J. Pers. Med. 2021, 11, 777.
47. Kriechling, P.; Roner, S.; Liebmann, F.; Casari, F.; Fürnstahl, P.; Wieser, K. Augmented reality for base plate component placement in reverse total shoulder arthroplasty: A feasibility study. Arch. Orthop. Trauma. Surg. 2020, 141, 1447–1453.
48. Kriechling, P.; Loucas, R.; Loucas, M.; Casari, F.; Fürnstahl, P.; Wieser, K. Augmented reality through head-mounted display for navigation of baseplate component placement in reverse total shoulder arthroplasty: A cadaveric study. Arch. Orthop. Trauma. Surg. 2021; published online ahead of print.
49. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G.; PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. Ann. Intern. Med. 2009, 151, 264–269.
50. McGuinness, L.A.; Higgins, J.P.T. Risk-of-bias VISualization (robvis): An R package and Shiny web app for visualizing risk-of-bias assessments. Res. Synth. Methods 2021, 12, 55–61.
51. Audenaert, E.; De Smedt, K.; Gelaude, F.; Clijmans, T.; Pattyn, C.; Geebelen, B. A custom-made guide for femoral component positioning in hip resurfacing arthroplasty: Development and validation study. Comput. Aided Surg. 2011, 16, 304–309.
52. Scott, J.W. Scott’s parabola. BMJ 2001, 323, 1477.