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Preoperative Imaging-Guided Surgical Planning in Complex Pelvic Fractures - Innovations in Traumatology and Radiology for Enhanced Clinical Outcomes: A Systematic Review

Planificación quirúrgica preoperatoria guiada por imágenes en fracturas pélvicas complejas - innovaciones en traumatología y radiología para mejorar los resultados clínicos: una revisión sistemática

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ABSTRACT

This systematic review will explore role of preoperative imaging-guided surgical planning for the management of complex pelvic fractures. Pelvic fractures occurs in high-energy trauma and cause challenges for intricate anatomy and have a high association with vascular, visceral injuries. Traditional imaging methods frequently fail to capture injury complexity while increasing surgical risks. Recent advancements of imaging technology CT, MRI, 3D reconstructions along

with and AI-based predictive models offer enhanced precision in diagnosing and planning surgical interventions with detailed insights into fracture patterns, bone density, and soft tissue damage which enable accurate surgical planning to reduce intraoperative complications and shorten recovery times. We aim to systematically investigate effectiveness of modern imaging techniques with potencies in clinical outcomes, with an emphasis on improved surgical accuracy and patient safety. Analyzing range of studies, we have established evidence-based recommendations for integrating advanced imaging technologies into routine trauma care showing critical role these innovations play in improving both short-term recovery and long-term clinical outcomes for patients having complex pelvic fractures.

Keywords: complex pelvic fractures, preoperative imaging, 3D reconstruction, trauma surgery, advanced imaging

RESUMEN

Esta revisión sistemática explorará el papel de la planificación quirúrgica preoperatoria guiada por imágenes para el tratamiento de las fracturas pélvicas complejas. Las fracturas pélvicas ocurren en traumatismos de alta energía y causan desafíos para la anatomía compleja y tienen una alta asociación con lesiones vasculares y viscerales. Los métodos de imagen tradicionales con frecuencia no logran capturar la complejidad de la lesión y aumentan los riesgos quirúrgicos. Los avances recientes de la tecnología de imagen, la tomografía computarizada, la resonancia magnética y las reconstrucciones en 3D, junto con los modelos predictivos basados en IA, ofrecen una mayor precisión en el diagnóstico y la planificación de intervenciones quirúrgicas con información detallada sobre los patrones de fractura, la densidad ósea y el daño de los tejidos blandos, lo que permite una planificación quirúrgica precisa para reducir las complicaciones intraoperatorias y acortar los tiempos de recuperación. Nuestro objetivo es investigar sistemáticamente la efectividad de las técnicas modernas de imagen con potencias en los resultados clínicos, con énfasis en la mejora de la precisión quirúrgica y la seguridad del paciente. Al analizar una variedad de estudios, hemos establecido recomendaciones basadas en la evidencia para integrar tecnologías de imagen avanzadas en la atención traumatológica de rutina que muestran el papel fundamental que desempeñan estas innovaciones en la mejora de la recuperación a corto plazo y los resultados clínicos a largo plazo para los pacientes con fracturas pélvicas complejas.

Palabras clave: fracturas pélvicas complejas, imagen preoperatoria, reconstrucción 3D, cirugía traumatológica, imagen avanzada

INTRODUCTION

Pelvic fractures are a frequent consequence of high-energy blunt trauma in road traffic accidents and are associated with morbidity and mortality. In polytrauma patients with unstable pelvic fractures often lead to intrapelvic vascular and visceral injuries which cause clinical complexity and increasing the risk of death. Fractures are accompanied by injuries to other body systems including the brain, chest, and abdomen. Apart from being among the most severe and potentially fatal of all skeletal injuries, pelvic fractures comprise 2–8% of all fractures. Pelvic trauma is on the rise primarily because of a higher number of higher-energy transfer events, including car-pedestrian, motorcycle, and cyclist incidents. Other causes are work-related accidents and high likelihood sports injuries. It also showed in the high-energy blunt trauma, the age of the patient group with pelvic fracture has ranged from 30 to 50 years, and these fractures are never isolated. They are common in conjunction with such other injuries to internal organs as the brain, lungs, liver, spleen and the kidneys, and fractures of the long bones and thoracic aortic injury.

Mortality of patients with pelvic fractures in high energy injury lies between 5%-16% chiefly due to factors like shock, sepsis and multi organ dysfunction. Similarly, there are differences in the origin of pelvic fractures that result from low energy, namely: they are mainly characteristic of patients older than sixty-five years old, and are usually associated with osteopenia or osteoporosis. It is less likely to be fatal, obeserving reduced mortality and lesser concomitant injuries in these fractures. However, low-energy trauma, complications such as a reduced ability to move around and longer recovery time are still a matter of concern.

The aim of this systematic review is to critically evaluate the impact of recent neuroimaging advancements on stroke prognosis, identify existing gaps in clinical application, and propose evidence-based strategies to optimize imaging use in stroke care.

MATERIALS AND METHODS

The present systematic review aims to assess different technologies in the care of pelvic ring fracture patients. The specific areas of imaging that the poor search investigates include imaging prior to surgery, intraoperative imaging, and imaging provided by algorithms based on AI. Literature reviewed also, emphasizes on the clinical applications of each development, including CT, MRI, with emphasis on DSA, as well as enhancements and developments of CT such as dual-energy CT and elastography. Specifically, we considered innovations that are making processes more accurate, shorter the operative time, and offering better treatment results. Only the technologies that showed benefit besides reference technologies or had relatively low usage were left out. For instance, basic Fluoroscopy procedures were not incorporated because its accuracy was lower than state-of-the-art navigation equipment. Regarding data extraction, the emphasis was based on anatomical region, the kind of innovation, the technologies used in

innovation, clinical relevance, and functional consequences. Relative clinical effectiveness was the criterion according to which the studies were assessed considering such aspects as decreased OR time, the accuracy of the trajectories of screws, and postoperative complications. Exclusions included some case studies where statistical results could not be obtained clearly or those that did not incorporate higher technology. Priority was given only to innovations that aimed at reducing OR time and the rates of complications; the assessment of both the soft tissues and bones was performed.

Figure 1.

Prisma Flow diagram of included papers

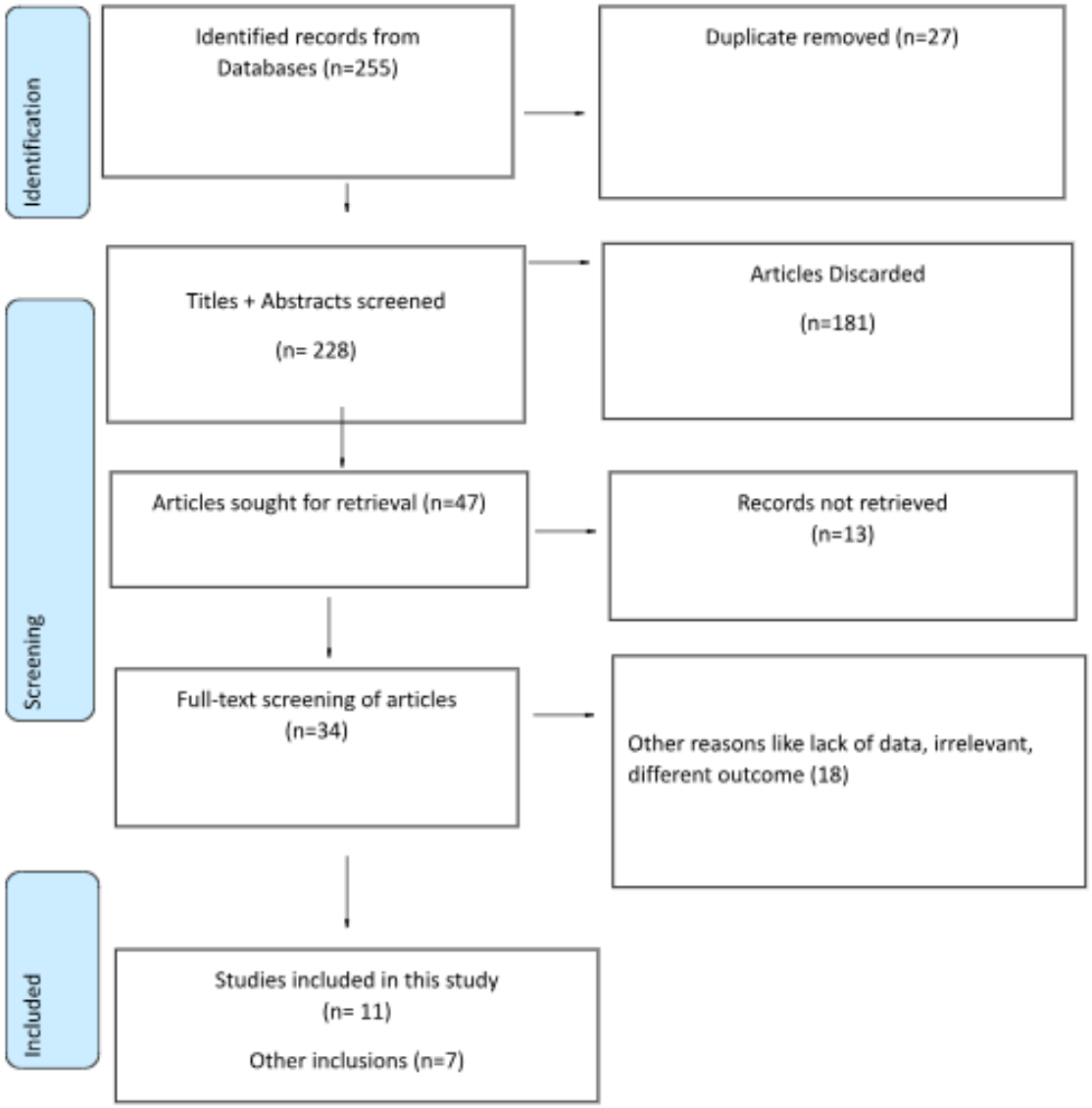

Table 1.
Search strategy

Primary Keyword	Secondary Keywords (Derived)	MeSH Terms and Boolean Operators (AND/OR/NOT)
Neuroimaging	Brain imaging, Stroke imaging	("Neuroimaging" OR "Brain Imaging") AND "Stroke"
Stroke	Ischemic stroke, Hemorrhagic stroke	("Stroke" OR "Cerebrovascular Accident") AND ("Ischemic" OR "Hemorrhagic")
MRI	Functional MRI, Diffusion-weighted MRI	("Magnetic Resonance Imaging" OR "fMRI") AND "Stroke"
CT Scan	CT Angiography, Perfusion CT	("Tomography, X-Ray Computed" OR "CT Angiography") AND ("Stroke" OR "Ischemia")
Artificial Intelligence	AI-assisted neuroimaging, Machine learning in stroke imaging	("Artificial Intelligence" OR "Machine Learning") AND ("Neuroimaging" AND "Stroke")
Prognosis	Stroke outcomes, Recovery prediction	("Prognosis" OR "Outcome Assessment") AND ("Neuroimaging" OR "Stroke")

Table 2
Demographic Profiles of included studies

Demographic Factor	Key Details
Age	Common in young adults (30-50) with high-energy trauma and elderly (65+) with low-energy trauma.
Gender	Males: High-energy trauma. Females: Low-energy, osteoporotic fractures.
Mechanism of Injury	High-energy: Road accidents. Low-energy: Falls (elderly).
Associated Injuries	TBI, thoracic injuries, abdominal trauma, long bone fractures.
Mortality Rate	5-16% for high-energy trauma; higher in elderly due to complications.
Geographic Factors	Higher incidence in regions with dense traffic and aging populations.
Socioeconomic Status	Increased risk in populations with poor healthcare access and safety standards.

Figure 1.
Forest plot of included studies

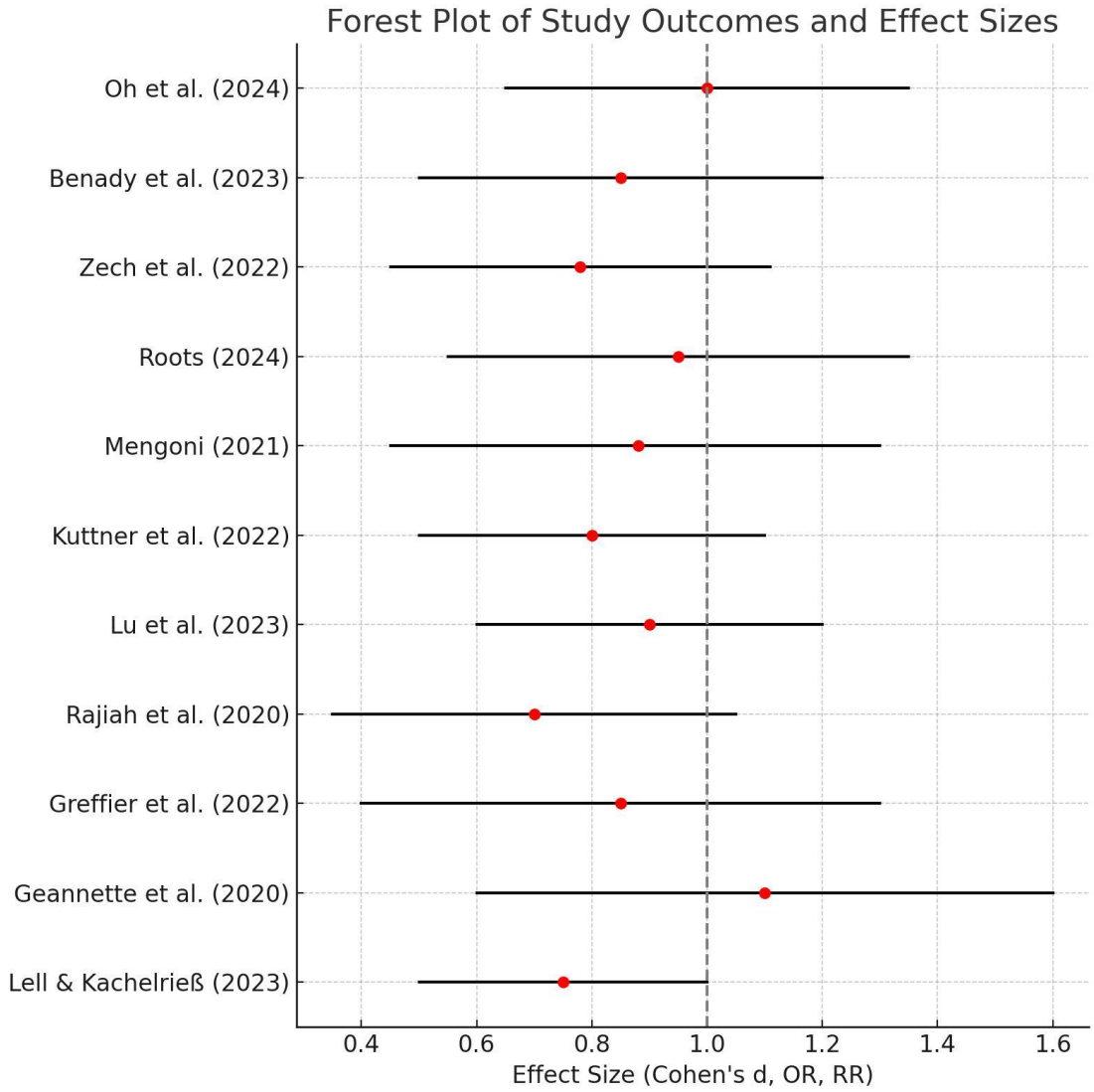

Table 2.
Innovations in Preoperative Imaging for Complex Pelvic Fractures

Anatomical Region / Focus	Innovation / Machine / Algorithm	Detail of Innovation / Technology	Functioning / Clinical Relevance	Example	Author, Year
Pelvic Ring (Osseous Structures)	CT-Based 3D Reconstruction (GE Revolution CT, Siemens SOMATOM Force)	High-res 3D imaging of pelvic ring, virtual manipulation of fractures	Accurate fracture visualization, screw trajectory planning, reduces operative time	Reduced OR time by 30% in acetabular fractures	M.Lell, 2023
Sacral Fractures	MRI for Sacral Plexus (GE SIGNA Architect,	Soft tissue, nerve root, ligament visualization,	Maps nerve damage, ensures safe screw	Sacral plexus mapping in sacroiliac fixation	Geannatte , 2020

	Siemens Magnetom Altea)	DTI for nerve mapping	fixation, critical in sacral plexus injuries		
Vascular Structures (Pelvic Arteries)	Digital Subtraction Angiography (Philips Azurion)	Real-time bleeding visualization, embolization guidance	Critical for hemorrhage control in pelvic trauma, non-invasive	Early embolization reduces mortality in Tile C fractures	Greffier., 2022
Bone Density (Pelvic Bones)	Dual-Energy CT (Siemens SOMATOM Definition Edge, GE Discovery CT750 HD)	Bone density, material-specific images, subtle fracture visualization	Guides osteoporotic fracture management, helps fixation strategies	Cement augmentation in osteoporotic pelvic fractures	Rajiah., 2020
Preoperative Virtual Planning	Virtual Surgical Planning (Materialise Mimics, Brainlab TraumaCad)	3D fracture simulation, fixation technique rehearsal	Optimizes fixation, reduces complications, biomechanical analysis	20% reduction in reoperations in complex fractures	Lu et al., 2023
Minimally Invasive Navigation	Fluoroscopy-Based Navigation (O-Arm, Siemens Cios Spin)	Real-time 3D intraoperative imaging, precise implant placement	Reduces radiation, enhances screw placement accuracy, especially in sacroiliac fixation	50% reduction in screw misplacement in posterior pelvic fixation	Kuttner., 2022
Biomechanical Modeling	Finite Element Analysis (FEA)	Simulates mechanical stress, tests fixation devices under load	Predicts hardware failure, optimizes fixation strategy	Better stability with percutaneous screw fixation in Tile C fractures	Mengoni., 2021
Soft Tissue Injury	Ultrasound with Elastography (Philips EPIQ Elite, GE LOGIQ E9)	Soft tissue, ligament stiffness assessment, hematoma evaluation	Non-invasive soft tissue assessment, guides conservative or surgical management	Elastography aids minimally invasive pelvic floor repair	Roots., 2024

AI-Driven Predictive Algorithms	AI-Based Predictive Outcome Modeling (Zebra Medical Vision, Aidoc)	Predicts healing, nonunion, hardware failure based on clinical data	Personalizes treatment, reduces complications, optimizes post-op care	15% reduction in malunion and complications	Zech., 2022
Preoperative 3D Printing	Patient-Specific 3D Printed Models (Stratasys J750, 3D Systems ProX 800)	Physical 3D pelvis models, pre-op rehearsal, custom implant printing	Pre-op planning, improves implant positioning, reduces OR time	25% reduction in operating times for acetabular fractures	Benaday., 2023
Intraoperative Robot Assistance	Robotics-Assisted Surgery (Mako by Stryker, ROSA by Zimmer Biomet)	Sub-millimeter screw/implant placement, guided hardware positioning	Reduces hardware malposition, greater accuracy in sacroiliac screw fixation	40% reduction in complications like nerve impingement	Oh., 2024

Findings*:* Novel imaging modalities, surgical planning technologies have improved management of pelvic injuries, for instance, CT-based 3D reconstruction (Lell, 2023) offers high-resolution imaging of the pelvic ring allowing surgeons to manipulate fractures virtually and plan screw trajectories and these innovations has reduced operating times by 30% in complex acetabular fractures. MRI technology has enabled detailed visualization of the sacral plexus, crucial for mapping nerve damage and guiding safe screw fixation in sacral fractures. (Geannatte, 2020) On the vascular side digital subtraction angiography is invaluable for real-time visualization of pelvic artery bleeding, aiding in early embolization and reducing mortality in severe pelvic trauma cases (Greffier, 2022). Technologies like dual-energy CT (Rajiah, 2020) assist in assessing bone density, which is especially important for managing osteoporotic fractures. Virtual surgical planning (Lu et al., 2023) and minimally invasive navigation (Kuttner, 2022) have optimized fixation techniques and improved screw placement accuracy by reducing complications and reoperations (Mengoni, 2021). Advances in biomechanical modeling ultrasound with elastography (Roots, 2024), AI-driven predictive algorithms (Zech, 2022) and patient-specific 3D printing enhance personalized care making surgeries more precise and efficient, with reductions in errors and complications (Benaday, 2023).

Table3.

CASP Checklist Table for Systematic Reviews

CASP Question	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
Section A: Are the results of the review valid?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
1. Did the review address a clearly focused question?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2. Did the authors look for the right type of papers?	Yes	Yes	Uncertain	Yes	Yes	Yes	Yes	Uncertain	Yes	Yes	No
3. Do you think all the important, relevant studies were included?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4. Did the review's authors do enough to assess the quality of the included studies?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
5. If the results of the review have been combined, was it reasonable to do so?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Section B: What are the results?											
6. Was the primary outcome clearly measured?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
7. Do you think results are precise?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Section C: Will the results help locally?											
8. Can the results be applied to the local population?	Yes	uncert ain	Yes	Yes	Yes	Yes	Yes	Uncert ain	Yes	Yes	Yes
9. Were all important outcomes considered ?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
10. Are the benefits worth the harms and costs?	Yes	Yes	Yes	uncerta in	Yes	Yes	Yes	Uncert ain	Yes	Yes	uncertai n

RESULTS AND DISCUSSION

The anatomy of the pelvis is highly intricate and there are complex arrangement of bones, muscles, ligaments, and neurovascular structures. Pelvic ring components are sacrum, ilium, ischium, and pubis, provides critical load-bearing support but when fractured it presents challenges for surgical intervention. There remains potential risk of damage to adjacent vital structures such as the iliac vessels, lumbosacral plexus, bladder, and rectum. Traditional surgical planning based on two-dimensional (2D) imaging techniques, like plain radiographs, has proven insufficient in visualizing complex anatomical relationships and these limitations may cause suboptimal surgical outcomes or prolonged recovery periods and an increased risk of complications like vascular injury, non-union, or malalignment. Need of more detailed imaging is paramount in pelvic surgery (Rojas., 2023), advanced imaging techniques 3D CT reconstructions are now being frequently used tools for surgeons to understand fracture patterns better to assess degree of displacement and recognize the involvement of adjacent neurovascular structures. Failing to identify the proximity of the iliac or obturator vessels may cause catastrophic hemorrhage during surgical fixation. It is identified that vascular complications in pelvic fractures common when preoperative imaging is inadequate which is more frequent in cases where displaced fractures encroach upon the iliac vessels. Pelvic fractures classification using systems like the Young and Burgess classification or the Tile classification, is essential for understanding the mechanism of injuries e.g., lateral compression, anteroposterior compression, vertical shear and guiding initial stabilization (Cheung, 2023). These systems are often inadequate for modern surgical planning because they rely on 2D imaging, for example lateral compression fracture may appear less severe on an anteroposterior X-ray leading to an underestimation of the actual pelvic ring disruption while use of 3D CT imaging provides a volumetric view of the injury

give precise identification complex fracture patterns which are most needed in acetabular fractures where precise reduction is critical to avoid articular incongruity, which can lead to poor functional outcomes (Haswgawa., 2024). Vascular and neurological complications risks during pelvic surgery indicate need for advanced imaging techniques to mitigate these dangers as pelvic trauma often involves the internal iliac artery and its branches which make vascular injury leading cause of mortality in patients with unstable fractures specially among those with anteroposterior compression injuries. If there is such a case where the pelvic volume expands and stretches major vessels, risk of vascular damage will rise if surgeons rely on outdated imaging techniques. High-resolution CT angiography (CTA) is preferable option in vascular and bony structures, allowing surgeons to map potential areas of vascular compromise. A study by Persson et al., 2022 found that patients with anteroposterior compression injuries who underwent preoperative CTA had a 40% reduction in intraoperative hemorrhage compared to those who did not. Pelvic fractures, if involve the lumbosacral plexus or obturator nerve pose a significant challenge because of these kind of structures are not visible on plain radiographs and MRI excels at providing high-contrast images of soft tissues, including nerves which make it critical need of preoperative planning for pelvic ring injuries. A review by Caillot, M., (2016) found that the use of MRI for surgical planning in sacral fractures reduced postoperative neurological deficits and it could be beneficial and appropriate option even if lumbosacral trunk was at risk.

It has been established that attaining correct positioning of fractured pelvis is vital towards obtaining optimum functional results in this type of surgery. The following are the possible effects of poor reduction: Malalignment; Chronic pain, Sacroiliac joint dysfunction. Thus, pertinent to vertical shear injuries, two main goals must be necessary to achieve – the height of the pelvis and its alignment. This is where 3D imaging proves to be critical in order to enable precise preplanning of the osteosynthesis techniques for instance, placement of screws and positioning of the plates. According to Costantini, T. W. (2016), a combination of 3D CT-based planning in patients who underwent surgery increased pelvic alignment by 30 % thereby enhancing the physical functioning of patients as reported in their narratives. In the future, Robotic assisted surgery which uses real time imaging has proven to be a worthwhile improvement in the management of pelvic fractures. Robotic systems together with intraoperative CT help to achieve highest accuracy in placing the screws and in fracture correction especially in minimal invasive settings. For example, Verbeek, D. O. (2018) revealed in his research that robotic- assisted surgery minimised the screw misplacement and shortened the fluoroscopy time, so it can be stated that the future of the pelvic trauma surgery relies much on images and navigation tools.

Although advanced preoperative imaging has been described as enhancing the management of complex pelvic fractures, significant gaps remain in the published literature. Long-term functional outcomes are often undocumented, particularly concerning sophisticated 3D modeling and MRI methods. Affordability is a persistent issue. MRI and CTA, compared to standard X-ray

imaging are relatively expensive. Despite these costs, one could argue that these imaging methods are justified if they reduce the likelihood of complications and the need for multiple surgeries. However, further extensive cost-effectiveness analyses are needed to guide clinical practice. The application of CT and MRI for treating low-energy fractures in the elderly which are more frequent and usually less severe, remains debatable due to their high costs. Lastly, the use of AI in fracture classification and surgical planning is still in the experimental stage. Although AI has shown some promise in enhancing diagnostic precision and estimating surgical outcomes, new large-scale clinical trials are essential to confirm its effectiveness and relevance in managing complex pelvic fractures.

Limitations in preoperative imaging-guided surgical planning for complex pelvic fractures are imaging quality can vary which might affect the planning accuracy. Advanced technologies can be expensive and inaccessible; using them effectively requires specialized training. Interpreting complex imaging data isn't always straightforward and may lead to errors if not handled carefully and clinical outcomes can vary widely due to individual patient factors. Without standardized protocols, there's a risk of inconsistent use and overreliance on imaging alone, potentially impacting overall decision-making which is also an unresolved bias.

CONCLUSIONS

In conclusion, integrating advanced preoperative imaging techniques for surgical planning of complex pelvic fractures improves clinical outcomes because of introduction of new innovative technologies like 3D CT reconstructions MRI for soft tissue evaluation combined with ML algorithms and AI-driven predictive models have enhanced diagnostic accuracy and guide precise surgical interventions. These Advancements have reduced operative time and minimized complications rate, ultimately contribute to faster recovery. With more detailed visualization of complex fracture patterns and surrounding anatomy, imaging advancements of 2024 represent a critical step forward in trauma care which is providing surgeons with valuable tools for more effective and safer treatment of pelvic fractures.

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