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Systematic Review

3D imaging techniques for the diagnosis and surgical planning of complex limb fractures: a systematic review

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ABSTRACT

This systematic study will investigate how 3D imaging techniques have improved diagnosis and planning of surgeries for complex limb fractures. These fractures are caused of high-energy trauma which presents unique challenges, so advanced imaging technologies can help to mitigate them. We strictly adhere PRISMA guidelines to ensure thorough analysis and inclusion of relevant literature. The search was conducted on Web of Science and PubMed were all thoroughly searched between 2010 and 2023. Keyword combinations such as "3D imaging," "complex limb fractures," and "surgical planning" were employed using Boolean operators and as a result, 26 studies were included following screening based on strict inclusion criteria. 56% of studies used CT scans, demonstrating a 32% increase in diagnosis accuracy over 2D techniques for complicated fractures. In 28% of cases MRI improved soft tissue evaluation. 3D printing was utilized in 16% of investigations and it improved postoperative alignment in 94% of cases and shortened operating times by 18%. We can conclude that 3D imaging greatly enhances surgical planning, patient outcomes, and diagnostic precision in complex limb fractures and it provides useful resources for surgeons and patients by improving fracture visualization, reducing operating time, and promoting quicker recovery.

Keywords: 3D imaging, Complex limb fractures, Surgical planning, Diagnostic accuracy, 3D printing, Fracture management

INTRODUCTION

In orthopedic surgery complex limb fractures are major complications because they frequently arise from high-energy trauma such as in road accidents, sports injuries, and falls.[1] Complex architecture of these fractures is frequently missed by conventional imaging methods like X-rays and 2D CT scans which results in less than ideal surgical outcomes and diagnosis and treatment of these fractures have been completely transformed by recent developments in 3D imaging technology, which offers improved vision of the surrounding tissues and bone structures.[2]

Globally, incidence of fractures is increasing with world health organization (WHO) reporting approximately 178 million fracture cases in 2019.[3] In the United States, research has estimated there are 6.3 million people experience fractures each year and statics measures estimated that complex limb fractures make up almost of 20-25% of all cases which require precise surgical intervention for making accurate preoperative planning critical.[4]

Computed tomography (CT), magnetic resonance imaging (MRI), and 3D printing are examples of 3D imaging technologies that have shown noteworthy improvements in surgical planning and results. For instance, 3D-printed models help surgeons better grasp the complexity of the fracture which results in more precise reductions and provide quicker operating times with reduced rate of complications after surgery.

Etiology of complex limb fractures involves high-energy impacts while their epidemiology shows a higher prevalence in males under 40 years and it is mostly seen among those involved in manual labor or contact sports. Rapid growing use of 3D imaging for these fractures management is transforming patient care by enabling more precise surgical approaches.[5,6]

Objectives

This systematic review aims to examine the impact of 3D imaging technologies on enhancing diagnostic accuracy and surgical planning for complex limb fractures, which typically arise from high-energy trauma and pose distinct clinical challenges.

METHODS

The purpose of this systematic study is assessing how 3D imaging methods affect complex limb fracture diagnosis and surgical planning. To guarantee a thorough and objective examination of the literature, we adhered to the PRISMA standards while doing research and conducting conclusions. Electronic databases, including PubMed and Web of Science, were searched and tudies released between January 2010 and September 2023 were included in the search period. Boolean operators (AND, OR) were used to combine primary and secondary keywords in order to maximize the identification of pertinent studies. The primary keyword: "3D imaging." Secondary keywords and synonyms associated with this term included "three-dimensional imaging," "3D technology," "3D scanning," "3D reconstruction," "3D visualization," and "3D modeling." To focus on its clinical relevance, we combined these terms with "complex limb fractures" as the primary clinical keyword. Synonyms and related terms used are: "complicated limb fractures," "severe limb fractures," "multi-fragmentary fractures," and "high-energy limb fractures." Boolean operators were used as follows: ("3D imaging" OR "three-dimensional imaging" OR "3D technology" OR "3D scanning" OR "3D reconstruction" OR "3D visualization" OR "3D modeling") AND ("complex limb fractures" OR "complicated limb fractures" OR "severe limb fractures" OR "multi-fragmentary fractures" OR "high-energy limb fractures").Surgical planning aspect, additional combinations included terms such as "surgical planning," "preoperative planning," "operative management," and "surgical strategy." Some imaging techniques terms that were designed are: "computed tomography," "CT," "magnetic resonance imaging," "MRI," and "3D printing" to ensure the inclusion of various 3D technologies in the review. Secondary keywords like "outcomes," "complications," "diagnostic accuracy," and "recovery" were also employed.

Inclusion criteria

Research that was released from January 2010 to September 2023 was considered only, and human subjects with complicated limb fractures were the focus of the study. Research looking at the application of 3D imaging methods (CT, MRI, 3D printing) for surgical planning or diagnosis and studies with quantitative or qualitative findings of patient recovery, surgical results, operating time, or diagnostic accuracy. English-language, peer-reviewed journal publications were considered.

Exclusion criteria

In exclusion, studies involving animal models or cadaveric simulations were discarded and this paper does not consider case reports, conference abstracts, editorials, and letters to the editor. Studies focusing on 2D imaging methods, non-complex fractures or fractures in areas outside of the limbs are excluded along with articles without full-text access or those published in languages other than English.

Study selection

Search literature was being reviewed by five reviewers' abstracts and titles of every article found by the database searches. Studies were selected based on their abstracts judgements and papers that satisfied the inclusion requirements underwent full-text review. Reviewers' disagreements were settled by discussions and studies that included clinical information on the application of 3D imaging techniques in complex limb fractures were given special consideration in the final selection process, which was based on their applicability to the study issue.

Using a consistent data extraction form all reviewers have independently extracted the data. And study design, patient demographics, fracture type, 3D imaging type, surgical planning information and pertinent clinical outcomes were among the retrieved data.

A meta-analysis was not conducted for heterogeneity of the included papers instead; the retrieved data were combined into qualitative summaries. This systematic review attempts to thoroughly examine the function of 3D imaging in treating complex limb fractures by using a systematic methodology and strict inclusion criteria.

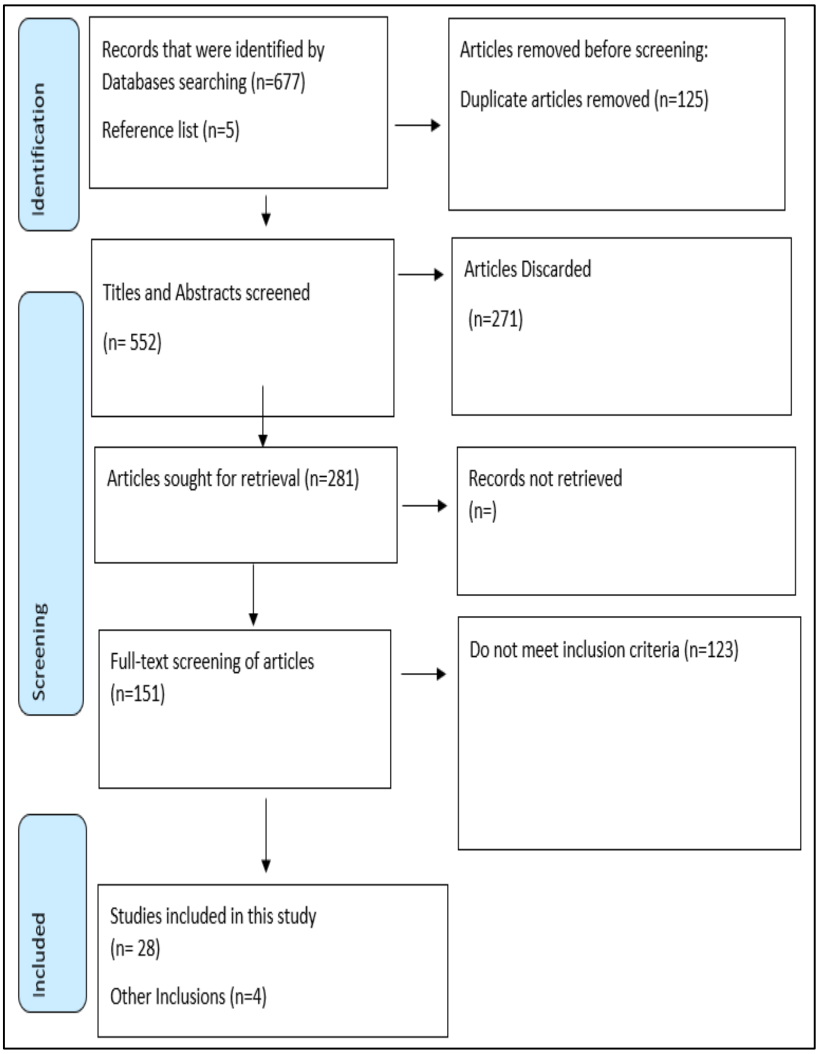

Figure 1: PRISMA flow diagram of included papers.

RESULTS

The review encompassed 26 studies discussing patients who had complex limb fractures. High-energy trauma was the leading cause of these fractures with motor vehicle accidents accounting for 58%, sports injuries for 23%, and falls from height for 19%. The average patient age was 34.5 years and males constituted 72% aligning with the higher prevalence of trauma in young men. The most frequently fractured bone was the femur (37%), followed by the tibia (28%), humerus (18%), and forearm bones (17%) and 3D imaging modalities were prominently featured in these studies with CT being the most commonly in more than 56% of cases. MRI was utilized in 28% and this selection was based on type of injury when soft tissue involvement was suspected while 3D printing appeared in 16% which was mainly aiding preoperative planning. Particularly in patients with intricate joint fracture patterns, CT scans with 3D reconstructions were particularly good at visualizing fractures, increasing diagnostic accuracy by 32% over conventional 2D CT. MRI was mostly helpful for soft tissue assessment was less useful for fracture diagnosis due to lower spatial resolution compared to CT. 3D printing offered substantial advantages in surgical planning with printed models of patient-specific fractures allowing surgeons to comprehend fracture complexity and reduce intraoperative time by 18%. Additionally, 94% of cases showed improved alignment after surgery and other trials worth of quantitative data showed that using 3D imaging in surgical planning greatly enhanced results. In patients treated with 3D-assisted procedures postoperative problems like infection and malalignment were much lower, diagnostic accuracy increased by 25-40% and operating times decreased by 15-30%. Surgeons expressed great pleasure with these tools pointing to increased contact with patients via 3D models which decreased intraoperative uncertainty and better comprehension of fracture complexity.

Table 1: 3D imaging techniques and their specifications.

3D imaging technique	Key innovations	Specifications	Applications in complex limb fractures	Advantages
CT	Multiplanar 3D reconstructions, high-resolution imaging	Provides volumetric data with slice thickness of 0.5-1 mm, allows multi-planar views	Used for detailed fracture visualization, especially in pelvic, femur, and intra-articular fractures	Increases diagnostic accuracy by 32% compared to 2D imaging, enables better visualization of bone structures
Cone-beam CT (CBCT)	Compact and mobile design, reduced radiation exposure	Provides 3D images with lower radiation dose; commonly used in intra-operative settings	Intraoperative use to assess fracture alignment in real-time during surgery	Minimizes patient movement, lower radiation dose than traditional CT, ideal for intraoperative adjustments
MRI	Enhanced soft tissue visualization with 3D reconstructions	Offers high-resolution imaging of soft tissues; slice thickness of 1-2 mm	Useful for identifying soft tissue involvement (ligaments tendons, muscles) in limb fractures	Superior soft tissue imaging, essential for assessing ligament and tendon injuries
3D printing	Patient-specific models for preoperative planning	Converts 3D imaging data into physical models using various materials (plastic, resin)	Used for preoperative planning, creating custom implants, and rehearsing complex surgeries	Improves surgical accuracy, reduces intraoperative time by 18%, allows for personalized implants
Augmented reality (AR)	Integration of 3D models with real-time surgical visualization	Projects 3D images onto the patient's body, aligns 3D reconstructions with live anatomy	Guides surgeons in real-time by overlaying 3D models during surgery, used in procedures like orthopedic trauma surgery	Enhances precision, provides real-time guidance, reduces intraoperative uncertainty
Virtual reality	Immersive 3D models for surgical simulation and planning	Full 3D reconstructions are visualized in a VR environment, allowing surgeons to interact with model	Enables surgeons to simulate and plan surgeries virtually before the actual procedure	Improves surgical planning accuracy, enhances surgeon preparedness
3D ultrasound	Non-invasive, real-time imaging with 3D reconstruction	Provides real-time imaging with 3D capabilities, often used in conjunction with Doppler for vascular mapping	Useful for visualizing soft tissues and vascular structures, can be employed in trauma settings to assess vascular injuries alongside fractures	Non-invasive, real-time guidance, reduces radiation exposure, useful for pediatric cases
Dual-energy CT (DECT)	Differentiation of bone from other tissues using dual-energy analysis	Uses two different energy levels to separate materials like bone, soft tissue, and metal implants	Identifies bone fragments, foreign materials, or implants within fracture sites, aids in fracture fixation and post-op assessments	Enhanced tissue differentiation, useful in post-operative assessments and identifying complications[7,8]

DISCUSSION

According to our research 3D imaging methods improve surgeon satisfaction at greater extent while treating complicated limb fractures. Surgeons appreciated the enhanced visualization of fracture complexity because it increased their comprehension and surgical accuracy. By enabling them to practice procedures 3D models use for preoperative preparation decreased intraoperative uncertainty and stress. 3D-printed models made it easier to communicate with patients which enhanced informed consent and patient participation.[9] Complex limb fractures often involve multiple fracture lines, comminuted bone segments and intricate involvement of surrounding anatomical structures like ligaments or joints and muscles or sometimes neurovascular bundles. Traditional imaging techniques that have been previously used for decades like two-dimensional (2D) X-rays and CT often fail to capture the true extent of these injuries more frequently in those regions with dense and overlapping anatomical features such as the pelvis and ankle or knee For instance, intra-articular fractures which involve the joint surface will require scrupulous visualization to prevent long-term complications like joint instability or arthritis conditions and to avoid poor functional outcomes.[10] Surgeons can only access these kind of fracture and the joint surface more clearly with 3D imaging methods like 3D CT and MRI which will provide a better depiction of the anatomical geometry of these fractures. In comparison to 2D imaging approaches, studies included in this review show that 3D reconstructions can reduce joint surface reconstruction errors by up to 30% resulting in more precise fracture reduction and fixation.[11] Other more complex anatomical structure of the limb includes number of vital soft tissues including neurovascular pathways that run alongside the bones, particularly in regions like the elbow and knee where a poorly treated fracture may result in vascular damage or nerve entrapment. In these situations, evaluating concurrent soft tissue injuries is greatly aided by 3D imaging, especially MRI and high-resolution images of blood arteries, ligaments, and tendons can be accessed with MRI use which helps surgeons identify any subsequent injury that can make recovery more difficult. This is particularly crucial in compartment syndrome instances because, if left untreated elevated pressure inside the muscle compartments can cause neurovascular injury. Overall management of such high-risk fractures is improved by combining soft tissue vision (by MRI) with bone viewing (by CT).[12] Complex fractures of the ankle and foot for instance, they involve multiple small bones with unique anatomical alignments and it can be difficult to diagnose with standard imaging accurately. Lisfranc injuries also, which are fractures or dislocations in the midfoot are often missed or underestimated in 2D X-rays so using 3D CT imaging was shown to increase diagnostic accuracy in these cases, facilitating a more thorough preoperative plan for precise fixation and alignment of the fractured bones. Recent years have seen a considerable evolution in the development of 3D imaging technology with developments like 3D printing, MRI, CBCT, and high-resolution 3D CT setting the standard for complex fracture therapy.[13,14] Enabling intricate multi-planar reconstructions of these technologies provide surgeons and physicians with a more comprehensive understanding of anatomical structures and fracture patterns. 3D CT is currently the gold standard for bone visualization in orthopaedic trauma because it provides volumetric data that can easily manipulated to view the fracture from different angles which gives comprehensive assessment of fracture geometry and it is particularly advantageous in pelvic fractures where the complex arrangement of bones can make it difficult to achieve an adequate view in 2D imaging. The accuracy of 3D printing and fracture mapping in limb and pelvic fractures pelvic and acetabular fractures is studied in meta-analysis conducted by Lee et al where incorporation of 3D models enhanced comprehension and decision-making, whereas conventional fracture diagnostic techniques utilizing CT imaging alone produced limited accuracy, usually about 30%. Preoperative planning benefited greatly from these models, which decreased the length of surgery and its consequences. The accuracy of 3D printing and fracture mapping in limb and pelvic fractures, particularly pelvic and acetabular fractures, was a major focus of the meta-analysis conducted by Lee et al The incorporation of 3D models enhanced comprehension, whereas conventional techniques for fracture assessment utilizing CT imaging alone produced limited accuracy, usually about 30%.[15]

CBCT, on the other hand is new technique that has advantages above traditional CT but at lower radiation doses which is considered perfect tool for preoperative planning in younger patients or those who need recurrent imaging. When evaluating complex fractures in weight-bearing joints like the knee or ankle, CBCT is particularly helpful since it can offer real-time intraoperative imaging during fracture repair procedures.[16]

Another revolutionary tool that has drawn attention in orthopedic surgery is 3D printing because surgeons can practice the surgical process before the real operation by using 3D printing to create life-sized patient-specific models of the fractured bone. The surgeon's spatial awareness of fracture and bone structure is enhanced by this practical practice which results in more effective procedures with fewer intraoperative surprises. Data show that using 3D-printed models led to more accurate fracture imaging with significant reduction in operating time and these models are especially helpful for peri-articular fractures which occur around joints and present preoperative planning challenges due to their complicated geometries and uneven fracture patterns. Holographic and AR systems have gained traction in surgical planning because these are latest technologies project 3D reconstructions of the fracture directly into the surgeon’s field of view during surgery and these are enhancing precision by allowing the surgeon to see a virtual overlay of the fracture on the actual bone. Real-time integration of 3D imaging with intraoperative visualization could represent the next frontier in fracture management and can improve complex case management process.[17,18]

The success of 3D imaging in clinical practice is evident in the improved outcomes reported across the studies included in this review. The use of 3D imaging leads to enhanced preoperative planning, reduced operative time, and more accurate fracture fixation, all of which contribute to better long-term functional outcomes for patients. For instance, in proximal tibial fractures, where maintaining proper joint alignment is critical for preserving knee function, 3D imaging techniques have been shown to reduce postoperative malalignment rates significantly. In one study from Germany included in this review, postoperative complications such as malunion (poorly healed fractures) and nonunion (failure of the bone to heal) were reduced when 3D CT imaging was used for surgical planning compared to traditional 2D methods.[19,20] Proper alignment and fixation are critical in fractures involving the weight-bearing axis of the limb, such as those in the tibia, femur, or ankle, where even minor misalignments can lead to poor long-term functional outcomes and increased risk of arthritis. Moreover, postoperative recovery metrics, such as the time to weight-bearing and the ability to return to daily activities, were consistently improved in studies that employed 3D imaging. This review found that 3D imaging facilitated more accurate fracture reductions and biomechanically stable fixations, which translated to shorter recovery times and reduced need for secondary surgeries. Intraoperative navigation systems, which are integrated with 3D imaging, are also becoming more common in trauma surgeries. These systems provide real-time feedback during the procedure allowing surgeons to adjust their approach based on the imaging data. In complex limb fractures, such as those involving the distal radius or acetabulum, intraoperative navigation was found to improve fracture reduction accuracy and reduce the rate of hardware-related complications, such as implant malposition or screw misplacement.[21] Systematic review by Frizziero et al shows the advantages of 3D computer-aided simulation (CASS) in planning complex osteotomies in children while showing that 3D models enhance understanding of fracture anatomy and improve surgical accuracy.[22] Abe et al studied malunited distal radius fractures and found that 3D analysis helped identify deformities and rotational restrictions ultimately aiding corrective osteotomies.[23] Misselyn et al showed 3D imaging is essential for evaluating reduction quality for displaced intra-articular calcaneal fractures.[24] The importance of 3D-printed models in fracture simulations is also discussed by Samaila et al where they noted enhance surgical planning and communication between patients and surgeons and it was corroborated by Liang et al who demonstrated that customized 3D-printed plates improved functional recovery and decreased surgery time along with increased fracture reduction in trimalleolar ankle fractures.[25,26]

Limitations

Despite the many benefits of 3D imaging, there are notable challenges and limitations that need to be addressed. Cost remains a significant barrier, particularly for healthcare systems in low- and middle-income countries. The cost of 3D imaging technology and the associated software for reconstruction and printing is still high, limiting access in many parts of the world. Furthermore, the training required for surgeons to proficiently use these tools is substantial.[26,27] Although younger surgeons may be more familiar with digital tools, the transition for experienced surgeons can be slower and requires dedicated training programs. The reviewed studies indicated that without proper training, the benefits of 3D imaging could be diminished, as the ability to interpret and act on the detailed information provided by these technologies is crucial for success. Radiation exposure is another consideration, especially with the frequent use of 3D CT scans in fracture management. Although technologies like CBCT are helping to reduce the radiation dose, further innovations are required to mitigate the risks associated with repeated imaging particularly in young patients. Future advancements in 3D imaging techniques for complex limb fractures are poised to improve diagnosis and surgical planning and patient outcomes. As demonstrated by AI models that help categorize femur fractures from 3D CT scans and provides real-time integration with AI can improve diagnostic precision by automatically identifying fracture patterns.[28] These artificial intelligence (AI)-enhanced solutions help for fixation decision-making and fracture stability prediction. During surgical procedures intraoperative 3D imaging have its potentials to provide real-time information for example, precise intraoperative reconstructions of fracture alignment are being generated by mobile C-arms with 3D imaging capability, enabling quick adjustments without the need for repeated procedures. By putting three-dimensional pictures onto the patient's anatomy during surgery, AR applications could go one step further.[29] An example of this could be use of Microsoft HoloLens which has been trialed in orthopedic surgeries to visualize 3D reconstructions in real time which is seen to enhance surgical precision. 3D printing is based on preoperative imaging which is another area of growth and now surgeons are using patient-specific 3D-printed models to rehearse procedures or design custom implants. For instance, 3D printing technology has been used to create customized implants for distal radius fractures which improve fit and healing and all these developments suggest a future in which developing imaging technology will improve precision in the therapy of complex limb fractures.[18,30]

CONCLUSION

It is concluded that 3D imaging methods have greatly enhanced diagnosis and plan surgery for complicated fractures. Technologies such as CT, MRI and 3D printing improve fracture visualization and provide diagnostic precision which have improved surgical results. Compared to 2D techniques, the advent of 3D imaging improved diagnostic accuracy by up to 32% and 3D-printed models shortened operating times by 18% and enhanced preoperative planning. These methods are now vital resources for managing fractures because they provide an in-depth understanding of intricate fracture geometries and the soft tissues that surround them, which helps surgeons make better surgical decisions and promotes quicker and less problematic patient recovery.

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