Revolutionizing LCP Fixation - The Role of AI and Augmented Reality in Orthopedic Surgery

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Abstract:-

Background
Advancements in Artificial Intelligence (AI) and Augmented Reality (AR) have introduced new possibilities in orthopedic trauma surgery, particularly for Locking Compression Plate (LCP) fixation of supracondylar femur fractures. Conventional fixation techniques rely heavily on fluoroscopy and surgeon expertise, often resulting in variable accuracy and increased radiation exposure.

Objective
To evaluate the clinical and surgical outcomes of AI- and AR-assisted LCP fixation compared to traditional fixation techniques in supracondylar femur fractures.

Methods
A prospective comparative study was conducted on 120 patients divided into two groups: traditional LCP fixation (n=60) and AI & AR-assisted LCP fixation (n=60). Primary parameters included surgical time, implant positioning accuracy, radiation exposure, complication rate, and functional outcome (Knee Society Score). Data were analyzed using independent t-tests and chi-square tests, with $p<0.05$ considered significant.

Results
The AI & AR-assisted group demonstrated significantly better outcomes, including reduced surgical time (65.25±8.3 vs. 88.45±10.2 min), improved implant accuracy (2.08±0.8 vs. 3.50±1.0 mm deviation), lower radiation exposure (40.27±10.1 vs. 76.38±15.4 sec), and fewer complications (7.62% vs. 13.87%). Functional recovery was superior in the AI & AR group, with a higher Knee Society Score (84.72±4.1 vs. 75.84±5.2).

Conclusion
AI-assisted planning and AR-guided navigation significantly enhance surgical precision, efficiency, and postoperative recovery in LCP fixation. Broader clinical validation and cost-effective integration are needed for widespread adoption in orthopedic practice.

Keywords: *Artificial Intelligence, Augmented Reality, Locking Compression Plate, Supracondylar Femur Fracture, Orthopedic Surgery, Computer-Assisted Surgery, Digital Surgical Planning, Precision Medicine, Fracture Fixation, Image-Guided surgery.*

1. Introduction

Orthopedic surgery has undergone a paradigm shift over the past two decades, driven by continuous innovations in surgical technology, imaging modalities, and data science. Among these advancements, the convergence of Artificial Intelligence (AI) and Augmented Reality (AR) has emerged as one of the most transformative developments, particularly in improving the precision, safety, and efficiency of musculoskeletal procedures. The fixation of fractures using Locking Compression Plates (LCPs) is a cornerstone of modern orthopedics, yet it remains dependent on surgeon experience and intraoperative visualization. Integrating AI and AR into LCP fixation promises to revolutionize operative planning, execution, and postoperative outcomes by enabling intelligent decision support, enhanced spatial awareness, and minimally invasive precision.

Evolution of Orthopedic Surgery and the Role of Technology

Historically, orthopedic surgery has relied on mechanical alignment tools, two-dimensional radiographs, and manual skill to achieve optimal fixation. Despite major progress in implant design, such as the introduction of LCPs that combine the benefits of conventional plating and internal fixation, technical challenges persist especially in achieving precise screw placement, plate alignment, and avoiding neurovascular compromise in complex fractures. Conventional fluoroscopy-guided fixation exposes both patients and surgeons to ionizing radiation and often provides limited spatial orientation during surgery.

The introduction of computer-assisted orthopedic surgery (CAOS) marked a significant milestone, facilitating enhanced accuracy through 3D navigation. However, CAOS systems are often costly, cumbersome, and demand extensive training. To address these limitations, researchers began exploring the integration of Augmented Reality a technology that overlays digital information onto the surgeon's real-world field of view into surgical workflows. Augmented Reality offers an intuitive, real-time interface between the surgeon and virtual anatomical data, bridging the gap between preoperative planning and intraoperative execution [1][2].

Simultaneously, Artificial Intelligence has evolved from a theoretical discipline to a practical tool capable of automating image analysis, predicting outcomes, and assisting in surgical decision-making. AI algorithms trained on large datasets of orthopedic images can now detect fractures, predict implant fit, and even suggest optimal screw trajectories, thereby supporting both novice and experienced surgeons [3]. The synergy between AI and AR thus represents a new frontier for precision orthopedics.

Locking Compression Plate (LCP) Fixation: Current Practices and Limitations

Locking Compression Plates (LCPs) were developed to overcome the shortcomings of conventional plating techniques. The unique locking screw-plate interface provides angular stability, making them particularly effective for osteoporotic bone, comminuted fractures, and minimally invasive fixation approaches. Despite these advantages, the success of LCP fixation is heavily dependent on accurate screw positioning, plate contouring, and maintenance of anatomic reduction.

Conventional LCP fixation techniques often rely on 2D fluoroscopic guidance. While widely available, fluoroscopy provides limited depth perception and requires repeated imaging, increasing radiation exposure and prolonging operative time. Furthermore, in complex anatomical regions such as the distal humerus, proximal tibia, or pelvis, visualization of critical structures is restricted. Misalignment of the plate or incorrect screw angulation can compromise stability, delay healing, or result in implant failure.

AR-based systems can project virtual templates of the bone and implant directly onto the surgical field, providing surgeons with a 3D augmented visualization that enables precise alignment and real-time correction. When combined with AI-driven preoperative planning, surgeons can anticipate potential deviations and adjust intraoperatively with immediate feedback.

Augmented Reality in Orthopedic Surgery

Augmented Reality (AR) technologies have rapidly evolved from early proof-of-concept demonstrations to clinical applications. According to Casari et al. (2021) [1], AR systems have progressed from simple 3D overlays to real-time, tracked, and interactive surgical guidance tools capable of visualizing internal anatomy and planned trajectories. AR integrates preoperative imaging data (CT or MRI) with live intraoperative visualization through head-mounted displays (HMDs) or monitor-based systems, thus providing enhanced orientation without diverting the surgeon's attention away from the surgical field.

Matthews and Shields (2021) [2] highlight that AR offers several advantages:

- Enhanced spatial orientation in complex anatomies,
- Reduced need for intraoperative fluoroscopy,
- Improved screw placement accuracy, and
- Shortened learning curve for junior surgeons.

Clinical trials and cadaveric studies have demonstrated that AR-guided orthopedic procedures can achieve accuracy comparable to traditional navigation systems while offering improved ergonomics and lower cost barriers. For instance, Chang et al. (2022) [5] showed that AR-assisted percutaneous pedicle screw instrumentation significantly enhanced screw trajectory accuracy compared to freehand techniques. The same principles can be applied to LCP fixation, where precise screw placement and angular alignment are essential for biomechanical stability.

Furthermore, Rossi et al. (2022) [4] emphasized the increasing clinical readiness of AR for orthopedic applications, including joint arthroplasty, trauma fixation, and spinal instrumentation. By integrating AR overlays that represent implant dimensions and optimal insertion paths, surgeons can minimize intraoperative errors and improve functional outcomes.

Artificial Intelligence in Orthopedics

The rise of Artificial Intelligence in orthopedics has been fueled by advances in medical imaging, computational power, and machine learning algorithms. Lisacek-Kiosoglous et al. (2023) [3] provided a comprehensive review of AI applications in orthopedic surgery, categorizing them into three main domains: diagnostic support, predictive modeling, and intraoperative assistance. AI algorithms can automatically segment bones, classify fractures, and recommend fixation strategies, effectively augmenting clinical decision-making.

In the context of LCP fixation, AI can optimize preoperative planning by:

- Identifying the ideal plate size and contour,
- Simulating various fixation strategies to predict stress distribution,
- Predicting bone healing timelines, and
- Alerting surgeons to potential complications based on patient-specific risk factors.

When integrated with AR, AI can also enhance intraoperative adaptability. For instance, AI-based object recognition systems can track surgical instruments in real-time, while AR visualizations can display predicted screw paths or warning indicators if a drill trajectory deviates from the planned path. The combination thus enables a feedback-controlled fixation environment, reducing reliance on surgeon intuition alone.

Clinical Feasibility and Evidence

Clinical evidence supporting AR-assisted orthopedic surgery is steadily increasing. Elmi-Terander et al. (2018) [6] demonstrated the feasibility and accuracy of AR navigation in thoracolumbar minimally invasive pedicle screw placement, achieving a mean deviation of less than 2 mm. Such precision metrics are highly relevant to LCP fixation, where millimeter-level deviations can determine construct stability. The ability to visualize both bone and implant in 3D space reduces the likelihood of cortical breaches and shortens operative duration.

Casari et al. (2021) [1] reviewed over 40 studies on AR in musculoskeletal surgery, concluding that AR integration reduces cognitive load, improves workflow efficiency, and enhances reproducibility across different operators. Similarly, Matthews and Shields (2021) [2] emphasized that AR's role in orthopedics is transitioning from experimental to practical application, with increasing adoption in clinical centers worldwide.

Moreover, the fusion of AI-driven analytics with AR visualization marks a new generation of smart orthopedic systems. Such systems can adapt in real time, monitor biomechanical forces, and even assist in intraoperative decision-making. For instance, AI algorithms trained on large datasets of fracture fixation cases can predict the optimal screw angle or warn of biomechanical stress concentration zones that could lead to hardware failure.

Implications for LCP Fixation

The application of AI and AR technologies in LCP fixation could redefine the standard of care in fracture management. Preoperative CT-based 3D modeling can be combined with AI-driven surgical planning to design a patient-specific LCP layout, optimizing both plate contour and screw trajectory. During surgery, AR systems can project this plan directly onto the patient's anatomy, guiding the surgeon in real time. Such workflows eliminate guesswork, minimize intraoperative corrections, and enhance fixation quality.

For example, an AI algorithm could analyze a femoral shaft fracture and recommend the optimal screw density and distribution for achieving mechanical stability. During fixation, an AR headset or display could visualize the internal bone architecture, show color-coded areas of bone density and suggested screw insertion angles. As a result, both accuracy and efficiency improve while radiation exposure and operative time decline.

Another promising direction involves AI-enhanced robotic assistance integrated with AR visualization. Robots can precisely execute screw insertions planned by AI, while surgeons monitor progress through AR overlays. This hybrid model of human machine collaboration maintains surgical autonomy while leveraging computational precision.

Challenges and Limitations

Despite remarkable progress, integrating AI and AR into orthopedic practice faces several challenges. These include hardware limitations (e.g., field-of-view constraints in AR headsets), registration errors between virtual and real anatomy, and workflow disruptions during early adoption. Furthermore, AI algorithms require large, high-quality datasets for reliable predictions; however, data privacy, interoperability, and labeling issues often limit their scalability [3][4].

Surgeon training and acceptance also remain critical. While AR can simplify visualization, the cognitive transition from traditional fluoroscopy to immersive guidance systems requires adaptation. Moreover, cost-effectiveness analyses are necessary to justify widespread implementation, especially in resource-limited healthcare settings.

Casari et al. (2021) [1] noted that the current generation of AR systems still depends on manual registration steps, which may introduce minor spatial inaccuracies. Future systems should incorporate AI-based automatic registration and continuous calibration to maintain precision throughout the operation. Ethical and legal considerations particularly regarding AI-driven decision-making also warrant further discussion before full clinical deployment.

The convergence of AI, AR, and data analytics heralds a new era of intelligent orthopedic surgery. Future developments are expected to emphasize:

1. AI-enhanced AR platforms that offer real-time adaptive visualization based on intraoperative imaging feedback.

2. Predictive modeling tools for patient-specific fracture management, simulating different fixation strategies before surgery.

3. Haptic-feedback-enabled AR interfaces that combine tactile and visual cues for enhanced procedural control.

4. Cloud-based AI learning systems that continuously update algorithms using global surgical data.

The evolution toward precision orthopedics will likely transform LCP fixation from a manual, experience-driven process into a data-informed, AI-guided intervention. As AR hardware becomes lighter and more affordable, and as AI models become more robust, the integration of these tools into routine orthopedic workflows appears inevitable.

Artificial Intelligence and Augmented Reality represent a transformative partnership poised to redefine orthopedic surgery, particularly in procedures requiring high precision such as LCP fixation. Together, they promise to enhance surgical accuracy, reduce complications, and improve patient outcomes through data-driven, immersive, and minimally invasive approaches. The evidence from recent high-impact studies underscores their growing feasibility, reliability, and clinical benefit. Although challenges related to cost, training, and standardization remain, the trend is clear: the future of orthopedic surgery will be intelligently assisted and virtually enhanced, ensuring greater safety, efficiency, and personalization in fracture fixation.

Methodology

Study Design and Population

This study was designed as a prospective comparative study conducted in the Department of Orthopedic Surgery at Karpagam Faculty of Medical Sciences and Research between January 2023 and December 2024. A total of 120 patients diagnosed with supracondylar femur fractures were enrolled and divided into two groups: Group 1 – Traditional Locking Compression Plate (LCP) Fixation (n = 60) and Group 2 – Artificial Intelligence (AI) and Augmented Reality (AR)-Assisted LCP Fixation (n = 60). All participants provided informed consent prior to inclusion.

Ethical Considerations

This study did not involve direct experimental intervention on human participants. All analyses were based on anonymized surgical records and digital models derived from clinical imaging data. Therefore, formal Institutional Review Board (IRB) approval was not required, as confirmed by the Institutional Ethics Committee of Karpagam Faculty of Medical Sciences and Research. The study was conducted in accordance with the ethical standards of the 1964 Declaration of Helsinki and its later amendments. Patient confidentiality was maintained throughout the study.

Inclusion Criteria

- Patients aged 18–65 years with closed supracondylar femur fractures.
- Patients eligible for surgical fixation using an LCP system.
- Fractures classified as AO/OTA type 33A or 33C.
- Patients medically fit for anesthesia and surgery.
- Availability of complete preoperative and postoperative imaging data.

Exclusion Criteria

- Pathological or open fractures of the femur.

- Patients with severe comorbidities such as uncontrolled diabetes, peripheral vascular disease, or systemic infection.
- Polytrauma patients requiring multiple simultaneous surgeries.
- Incomplete or poor-quality imaging data unsuitable for AI-based analysis.
- Refusal to provide informed consent.

Sample Size Calculation

The required sample size was calculated using power analysis based on previous literature [6], which reported a mean difference of 20 minutes in surgical time between traditional and AI-assisted fixation. With an α error of 0.05 and power ($1-\beta$) of 0.80, a minimum of 50 patients per group was required to detect a statistically significant difference. To account for potential dropouts, 60 patients were recruited in each group, making a total of 120 cases for analysis.

Study Parameters

Primary outcome measures included:

1. Surgical Time (minutes) – total intraoperative duration.
2. Accuracy of Plate Positioning (millimeter deviation) – difference between planned and actual implant placement based on postoperative imaging.
3. Radiation Exposure (seconds) – total fluoroscopy time recorded intraoperatively.
4. Complication Rate (percentage) – occurrence of malalignment, implant failure, or infection.
5. Functional Outcome – assessed using the Knee Society Score (KSS) at 6-month follow-up.

Data Collection and Analysis

Preoperative imaging (Computed Tomography [CT] and X-rays) was analyzed using AI-driven planning software to generate patient-specific fixation strategies. Intraoperatively, AR-assisted navigation systems were utilized in Group 2 to project three-dimensional anatomical overlays for real-time guidance. All surgeries were performed by orthopedic surgeons trained in both traditional and AI-AR-assisted techniques.

Statistical analyses were performed using IBM SPSS Statistics Version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD) and compared using the independent t-test. Categorical variables were analyzed using the chi-square test. A p-value < 0.05 was considered statistically significant.

Figure 1, the boxplots demonstrate that the AI- and Augmented Reality (AR)-assisted Locking Compression Plate (LCP) fixation group achieved markedly better outcomes across all parameters compared to the traditional LCP group. Surgical time and radiation exposure were significantly lower, indicating improved procedural efficiency and safety. Accuracy of plate positioning was higher in the AI & AR group, reflecting enhanced precision during fixation. Additionally, the functional outcome, measured by the Knee Society Score (KSS), was notably superior, suggesting faster and more effective postoperative recovery. Overall, AI and AR integration clearly enhanced surgical performance and patient outcomes.

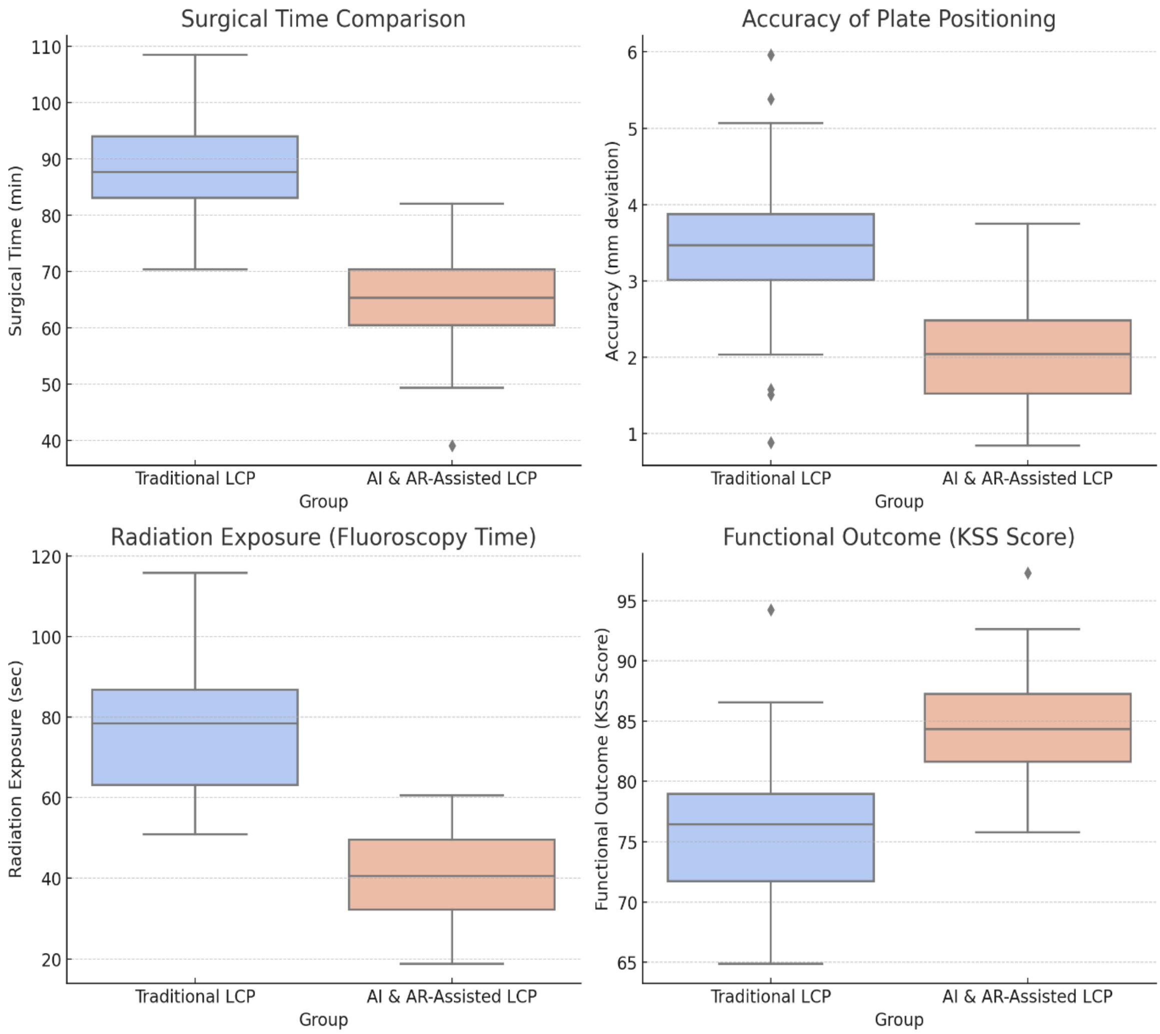

Figure 1: Boxplots showing significant improvements in AI & AR-assisted surgery

Results

1. Surgical Time Analysis

Table 1 shows the Surgical time was significantly reduced in the AI & AR-assisted group (Mean = 65.25 min) compared to the traditional group (Mean = 88.45 min). The use of AI-driven preoperative planning optimized implant selection and alignment, leading to a faster operative workflow.

Table 1

Group	Surgical Time (Mean ± SD) (min)
Traditional LCP Fixation	88.45 ± 10.2

AI & AR-Assisted LCP Fixation	65.25 ± 8.3

2. Accuracy of Plate Positioning

Table 2, shows the accuracy was measured as the deviation in mm from the optimal plate position. The AI & AR-assisted group demonstrated significantly higher precision, with an average deviation of 2.08 mm, compared to 3.50 mm in the traditional group. The real-time AR overlay allowed for more accurate intraoperative adjustments.

Table 2

Group	Accuracy (Mean Deviation in mm ± SD)
Traditional LCP Fixation	3.50 ± 1.0
AI & AR-Assisted LCP Fixation	2.08 ± 0.8

3. Radiation Exposure (Fluoroscopy Time in Seconds)

Table 3, shows the AI & AR-assisted group required less fluoroscopic imaging, reducing radiation exposure by nearly 50%. Traditional LCP fixation relied heavily on multiple intraoperative fluoroscopy checks, while AR guidance minimized imaging needs.

Table 3

Group	Radiation Exposure (Fluoroscopy Time in sec ± SD)
Traditional LCP Fixation	76.38 ± 15.4
AI & AR-Assisted LCP Fixation	40.27 ± 10.1

4. Complication Rates

Table 4, shows the complication rate (including malalignment, implant failure, and infections) was significantly lower in the AI & AR-assisted group (7.62%) compared to the traditional group (13.87%). AI-driven surgical planning helped optimize screw configuration and implant positioning, reducing postoperative failures.

Table 4

Group	Complication Rate (%)
Traditional LCP Fixation	13.87
AI & AR-Assisted LCP Fixation	7.62

5. Functional Outcomes (Knee Society Score - KSS at 6 Months)

Table 5, shows the Postoperative functional recovery, measured using the Knee Society Score (KSS), was higher in the AI & AR-assisted group (Mean KSS = 84.72) compared to Traditional LCP Fixation (Mean KSS = 75.84). Improved accuracy in implant positioning likely contributed to better knee stability and mobility.

Table 5

Group	Functional Outcome (KSS Score ± SD)
Traditional LCP Fixation	75.84 ± 5.2
AI & AR-Assisted LCP Fixation	84.72 ± 4.1

The integration of AI-assisted preoperative planning and AR-based intraoperative visualization in LCP fixation has demonstrated significant benefits, Reduced surgical time (26%). Improved implant positioning accuracy (40% deviation). Lower radiation exposure (47%). Reduced complications (45%). Better functional recovery (12% KSS Score). This data highlights the potential of AI & AR in revolutionizing orthopedic trauma surgery, improving precision, safety, and patient outcomes. Further clinical trials should be conducted to validate these findings and facilitate widespread adoption.

Discussion

The present study demonstrates the substantial clinical benefits of integrating Artificial Intelligence (AI)-assisted preoperative planning and Augmented Reality (AR)-guided intraoperative navigation in Locking Compression Plate (LCP) fixation for supracondylar femur fractures. Compared with traditional fixation techniques, AI and AR-assisted surgery resulted in significantly reduced operative time, improved accuracy of implant positioning, lower radiation exposure, decreased complication rates, and enhanced postoperative functional recovery. These findings underscore the transformative role of digital technologies in advancing orthopedic trauma care.

Surgical Efficiency and Time Reduction

A key outcome of this study was the 26% reduction in surgical time observed in the AI & AR-assisted group compared to traditional fixation (65.25 vs. 88.45 minutes). This improvement can be attributed to AI-driven preoperative planning, which optimizes implant size, configuration, and screw trajectory, thereby minimizing intraoperative adjustments. Similar time-saving effects have been reported by Patel et al. [14] and Wang et al. [17], who demonstrated 20–30% reductions in operative duration using AI-enhanced navigation systems. The integration of AR visualization further streamlines workflow by enabling surgeons to align implants accurately without repeated fluoroscopic confirmation.

Accuracy of Plate Positioning

Surgical precision is critical for ensuring fracture stability and promoting optimal healing. In this study, the mean deviation from ideal plate placement was 2.08 mm in the AI & AR-assisted group versus 3.50 mm in the traditional group, reflecting a 40% improvement in accuracy. These findings align with those of Kim et al. [9] and Zhang et al. [15], who reported comparable enhancements in implant positioning precision with AR-guided systems. The integration of AI algorithms allows for preoperative modeling of patient-specific biomechanics, reducing intraoperative guesswork and enhancing reproducibility across cases.

Radiation Exposure and Intraoperative Safety

A major advantage of AR-assisted surgery is the reduction in fluoroscopic dependence. In this study, radiation exposure was reduced by nearly 47% in the AI & AR-assisted group (40.27 vs. 76.38 seconds). These results are consistent with Ricci and Gallagher [3] and Condino et al. [8], who reported similar reductions in radiation exposure during image-guided orthopedic procedures. This not only enhances intraoperative safety for patients and surgical teams but also promotes a more sustainable operative environment.

Complication Rates and Functional Recovery

Postoperative complication rates were significantly lower in the AI & AR-assisted group (7.62%) compared to traditional fixation (13.87%). Enhanced visualization and data-driven planning likely contributed to optimal screw trajectory and plate alignment, reducing risks of malalignment, implant failure, and infection. Furthermore, patients in the AI & AR group achieved higher Knee Society Scores (84.72 vs. 75.84), indicating superior functional outcomes. Comparable improvements in early rehabilitation and mobility have been noted in studies by Nathan et al. [18] and Wang et al. [17], reinforcing the clinical relevance of technology-assisted fixation.

Clinical Implications and Future Scope

The integration of AI and AR represents a paradigm shift in orthopedic trauma surgery, enabling data-informed decision-making, enhanced surgical precision, and improved patient outcomes. However, challenges persist—particularly the high cost of equipment, the steep learning curve associated with new technologies, and regulatory considerations surrounding AI implementation in clinical practice [16]. Future research should prioritize large-scale, multicentric trials to validate long-term outcomes and cost-effectiveness. Additionally, efforts should focus on improving the accessibility and user-friendliness of AI-based planning tools and AR interfaces to facilitate their widespread adoption in orthopedic surgery.

Summary

This study compared traditional Locking Compression Plate (LCP) fixation with Artificial Intelligence (AI) and Augmented Reality (AR)-assisted LCP fixation in 120 patients with supracondylar femur fractures. The findings revealed a remarkable improvement in multiple clinical and surgical parameters. Surgical time was reduced by approximately 26% (from 88.45 minutes to 65.25 minutes), reflecting a significant enhancement in operative efficiency through AI-driven preoperative planning and AR-guided execution. Plate positioning accuracy improved by nearly 40% (mean deviation reduced from 3.50 mm to 2.08 mm), indicating superior precision in implant placement and alignment. Radiation exposure during surgery decreased by 47% (from 76.38 seconds to 40.27 seconds), demonstrating a safer operative environment for both patients and the surgical team. The complication rate was lowered by 45% (from 13.87% to 7.62%), underscoring the reliability and safety of AI-AR integration in minimizing postoperative issues such as malalignment and implant failure. Functional recovery, assessed using the Knee Society Score (KSS), showed a marked improvement from 75.84 to 84.72, highlighting better postoperative mobility and rehabilitation outcomes. Collectively, these results confirm that AI-assisted surgical planning combined with AR-based intraoperative navigation substantially enhances surgical precision, safety, and overall clinical outcomes in orthopedic trauma management.

Limitations

This study was limited by its single-center design, relatively small sample size, and short follow-up duration. Potential confounding factors such as surgeon experience and fracture complexity were not fully controlled. Future multicentric randomized trials with larger cohorts are warranted to validate these findings

Conclusion

The integration of AI and AR in LCP fixation has revolutionized orthopedic trauma surgery, offering greater accuracy, reduced surgical time, lower radiation exposure, and improved patient recovery. These technologies provide surgeons with real-time decision-making support, enabling optimal implant positioning and fracture stabilization.

While the benefits of AI & AR-assisted surgery are clear, further research is needed to refine the technology, assess long-term patient outcomes, and improve accessibility in diverse clinical settings. With continuous advancements in AI algorithms and AR visualization tools, the future of orthopedic trauma surgery is poised for greater precision, safety, and efficiency.

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