Original Research

BIOMECHANICS OF LOCKING PLATE FIXATION IN OSTEOPOROTIC FRACTURES: A PROSPECTIVE CLINICAL STUDY

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ABSTRACT

Background: Osteoporotic fractures are increasingly prevalent in the aging population and present significant challenges in orthopedic management due to reduced bone mineral density, poor screw purchase, and a higher risk of fixation failure. Conventional plating techniques often fail to provide adequate stability in osteoporotic bone. Locking plate systems, functioning as fixed-angle constructs, have emerged as a biomechanically superior alternative by providing angular stability and improved load distribution independent of bone quality.

Aim: To evaluate the biomechanical effectiveness, clinical outcomes, and factors influencing the success of locking plate fixation in osteoporotic fractures.

Materials and Methods: This prospective observational study was conducted at a tertiary care centre in Dindigul and included 135 patients aged ≥50 years with confirmed osteoporosis (DEXA T-score ≤ -2.5) who underwent locking plate fixation for long bone fractures over a 24-month period. Demographic data, fracture characteristics, bone mineral density, and implant-related parameters were recorded. Patients were followed up for 12 months with periodic clinical and radiological evaluation. Primary outcomes included fracture union and implant stability, while secondary outcomes included functional scores (DASH/LEFS) and complication rates. Statistical analysis was performed using SPSS version 25. Continuous variables were expressed as mean ± standard deviation, and categorical variables as frequencies and percentages. Chi-square test, independent t-test, and multivariate logistic regression analysis were used to identify predictors of fixation failure, with $p < 0.05$ considered statistically significant.

Results: The mean age was 68.2 ± 7.5 years, with female predominance (64.4%). Radiological union was achieved in 91.1% of cases, with a mean union time of 16.4 ± 3.2 weeks. Complications occurred in 14.8% of patients. Functional outcomes were good to excellent in 74.1% of cases. Severe osteoporosis, suboptimal screw density, and fracture comminution were identified as independent predictors of fixation failure ($p < 0.05$).

Conclusion: Locking plate fixation provides biomechanically stable and clinically effective management of osteoporotic fractures. Optimal surgical technique and implant configuration are essential to achieve favorable outcomes and minimize complications.

Keywords: Osteoporosis, Locking Plate, Biomechanics, Fracture Fixation, Bone Mineral Density.

INTRODUCTION

Reduced bone mass and degeneration of bone Microarchitecture are the hallmarks of osteoporosis, a degenerative systemic skeletal condition that increases bone fragility and fracture susceptibility. With an increasing incidence brought on by longer life expectancies and sedentary lifestyles, it is a significant global health concern, especially in the older population.[1] Osteoporotic fractures are linked to considerable morbidity, death, and healthcare costs. They most frequently affect the proximal humerus, distal radius, vertebral bodies, and hip.[2]

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Orthopedic surgeons face a special challenge when managing osteoporotic fractures because the quality of the bone is impaired. Osteoporotic bone's decreased density and structural integrity seriously diminish conventional implants' ability to hold.3 Conventional fixation methods rely on frictional force between the plate and the surface of the bone, which is frequently insufficient in patients with osteoporosis. This can result in issues such delayed or non-union, screw loosening, implant failure, and varus collapse.[4]

Locking plate technology has become a significant development in fracture fixation to overcome these constraints.

Because the screws lock into the plate to form a fixed-angle framework, locking plates are fundamentally different from traditional plating systems.

This design reduces reliance on bone quality for stability by combining the plate-screw system into a single stable unit. Locking plates thus serve as internal fixators, supplying angular stability and preserving fracture alignment even in bone with severe osteoporosis.[5]

Locking plate systems have a number of benefits from a biomechanical standpoint. These include better load distribution throughout the structure, a lower chance of screw pull-out, periosteal blood supply preservation because there is less plate-bone contact, and increased stability in comminuted fractures thanks to bridge plating procedures. Because of these characteristics, locking plates are especially useful for osteoporotic fractures, where secure fixation is frequently challenging.[6]

Clinical results of locking plate fixation vary greatly depending on a number of parameters, such as fracture pattern, bone mineral density, implant configuration, and surgical technique, despite these theoretical and experimental advantages. Fixation failure can result from improper screw placement, insufficient plate length, and subpar screw density. Additionally, in clinical practice, problems such screw cut-out, implant fracture, and loss of reduction are still being recorded.[7]

Prospective clinical studies that link these biomechanical concepts with actual outcomes in osteoporotic patients are still needed, despite the fact that many biomechanical research have shown the advantages of locking plates in laboratory conditions.

Optimizing treatment strategies requires an understanding of the link between implant mechanics, surgical technique, and clinical outcomes.[8]

In order to assess the biomechanical efficacy and clinical results of locking plate fixation in osteoporotic fractures, the current study was created, with a focus on finding variables that affect fixation stability, fracture healing, and functional recovery.[9]

MATERIALS AND METHODS

Study Design and Setting

This prospective observational study was conducted in the Department of Orthopedics at a tertiary care centre in Dindigul over a period of 24 months, from January 2024 to December 2025.

The study aimed to evaluate the biomechanical performance and clinical outcomes of locking plate fixation in osteoporotic fractures.

Study Population

A total of **135 consecutive patients** diagnosed with osteoporotic fractures and treated with locking plate fixation were included in the study.

A consecutive sampling technique was adopted to minimize selection bias and ensure representation of real-world clinical scenarios.

Sample Size Calculation

The sample size of 135 patients was determined based on an anticipated fracture union rate of approximately 85%, with a confidence level of 95% and allowable error of 7%. The sample size was also considered adequate for performing multivariate statistical analysis to identify predictors of fixation failure.

Inclusion Criteria

- Patients aged ≥ 50 years.
- Radiologically confirmed osteoporotic fractures.
- Bone Mineral Density (BMD) T-score ≤ -2.5 (DEXA scan).
- Closed fractures of long bones (proximal humerus, distal radius, femur, tibia).
- Patients undergoing surgical fixation using locking plate systems.
- Patients willing to provide written informed consent and comply with follow-up.

Exclusion Criteria

- Open fractures (Gustilo-Anderson Grade II and III).
- Pathological fractures secondary to malignancy.
- Polytrauma patients requiring multiple surgical interventions.
- Previous surgery at the fracture site.
- Patients with metabolic bone diseases other than osteoporosis.
- Patients unwilling or unable to complete follow-up.

Preoperative Assessment

All patients underwent detailed clinical and radiological evaluation. Bone mineral density was assessed using Dual-Energy X-ray Absorptiometry (DEXA). Fractures were classified based on standard classification systems relevant to the anatomical site (e.g., AO/OTA classification). Baseline demographic data including age, gender, comorbidities (diabetes, hypertension), and mechanism of injury were recorded.

Surgical Technique

All procedures were performed under standard aseptic conditions by experienced orthopedic surgeons. The following principles of locking plate fixation were uniformly applied:

- Minimally invasive or open reduction depending on fracture pattern
- Preservation of soft tissue and periosteal blood supply
- Use of anatomically contoured locking plates
- Indirect reduction techniques in comminuted fractures (bridge plating)
- Fixation using locking screws to achieve angular stability
- Maintenance of optimal screw density (40–60%)
- Adequate plate length to distribute mechanical stress

In selected cases with severe osteoporosis, adjunctive techniques such as bone grafting or augmentation were considered.

Postoperative Management

Postoperative protocols included early mobilization depending on fracture stability and patient tolerance. Passive and active range-of-motion exercises were initiated as per standard rehabilitation guidelines. Weight-bearing was gradually progressed based on radiological evidence of fracture healing.

Data Collection

Data were collected using a structured proforma similar in systematic approach to standardized clinical studies. The following parameters were recorded:

Demographic Variables

- Age
- Gender
- Comorbidities

Clinical and Biomechanical Variables

- Bone mineral density (T-score)
- Fracture type and classification
- Plate length and type
- Number and configuration of screws
- Screw density
- Quality of fracture reduction

Outcome Measures

1. **Radiological Union:** Defined as bridging callus formation across at least three cortices on X-ray.
2. **Time to Union:** Measured in weeks from surgery to radiological healing.
3. **Functional Outcome:** Assessed using validated scoring systems (DASH for upper limb, LEFS for lower limb fractures).
4. **Implant Stability:** Evaluated based on absence of screw loosening, plate breakage, or loss of reduction.
5. **Complications:** Including infection, implant failure, malunion, and non-union.

Follow-up Protocol

Patients were followed up at regular intervals:

- 6 weeks
- 3 months
- 6 months
- 12 months

At each visit, clinical examination and radiological assessment were performed to evaluate fracture healing and functional recovery.

Operational Definitions

- **Union:** Radiological evidence of bridging callus with painless weight-bearing.
- **Delayed Union:** Absence of healing beyond expected time (16–20 weeks).
- **Non-union:** Failure of fracture healing after 9 months.
- **Implant Failure:** Screw loosening, plate breakage, or loss of fixation.
- **Optimal Screw Density:** Ratio of inserted screws to available plate holes between 0.4 and 0.6.

Data Confidentiality

All patient data were anonymized using unique identification numbers. Records were stored securely in password-protected systems accessible only to the research team. Confidentiality was maintained throughout the study in accordance with institutional guidelines.

Ethical Considerations

The study was conducted at a tertiary care centre in Dindigul. The study protocol was approved by the Institutional Ethics Committee prior to initiation. Written informed consent was obtained from all participants. The study was carried out in accordance with the principles of the Declaration of Helsinki.

Statistical Analysis

Data were entered into Microsoft Excel and analyzed using SPSS version 25.0. Continuous variables were expressed as mean ± standard deviation (SD), while categorical variables were presented as frequencies and percentages.

Inferential statistical analysis included:

- **Chi-square test** for association between categorical variables
- **Independent t-test** for comparison of means
- **Multivariate logistic regression analysis** to identify independent predictors of fixation failure

A p-value of < 0.05 was considered statistically significant.

RESULTS

A total of **135 patients** with osteoporotic fractures treated with locking plate fixation were included in this prospective study. The mean age of the study population was **68.2 ± 7.5 years**, indicating a predominance of elderly patients. The mean time to fracture union was **16.4 ± 3.2 weeks**.

Demographic Characteristics of Study Participants

The majority of patients belonged to the age group of 61–70 years (43%), followed by patients above 70 years (33.3%). Females constituted a larger proportion of the study population (64.4%), reflecting the higher prevalence of osteoporosis among postmenopausal women.

Table 1. Demographic Characteristics of Study Participants (N = 135)

Variable	Frequency (n)	Percentage (%)
Age Group (years)		
50–60	32	23.7
61–70	58	43
>70	45	33.3
Gender		
Male	48	35.6
Female	87	64.4

Table Notes: Data are presented as frequency (n) and percentage (%) of the total study population (N = 135). Age and gender distribution reflect the epidemiological pattern of osteoporotic fractures.

Figure 1. Demographic Distribution of Study Participants

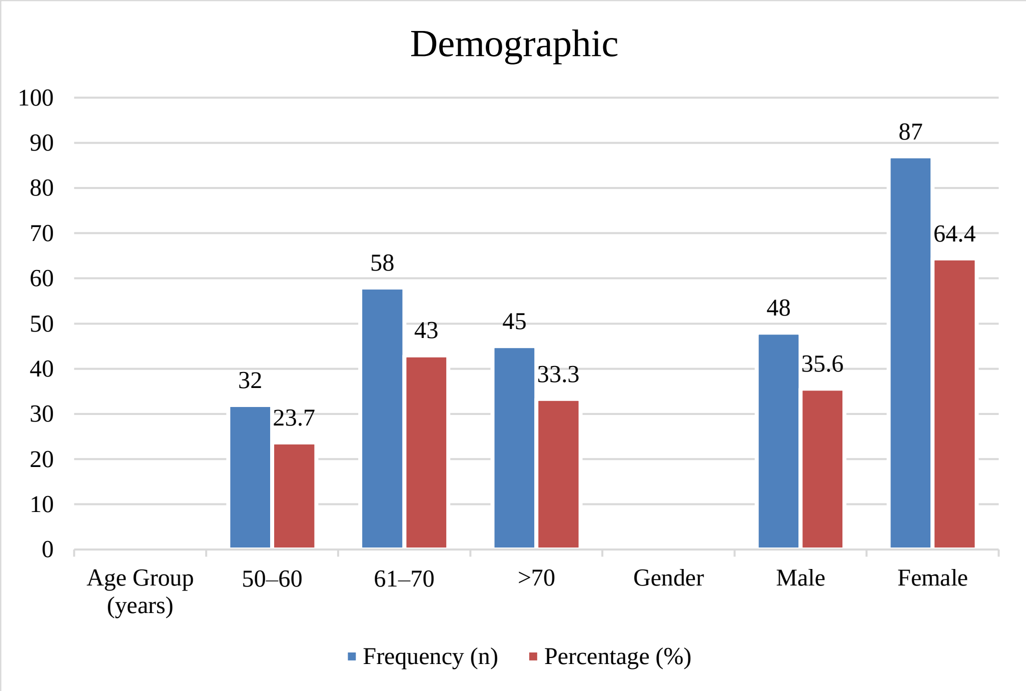

Figure Note: Majority of patients were aged 61–70 years, followed by those above 70 years. Female predominance was observed. This reflects the higher prevalence of osteoporosis in elderly women.

Distribution of Fracture Types

Distal radius fractures were the most common (31.1%), followed by proximal humerus fractures (28.1%). Femur and tibia fractures accounted for 22.2% and 18.5% respectively. This distribution highlights the susceptibility of metaphyseal regions to osteoporotic fractures.

Table 2. Distribution of Fracture Types

Fracture Site	Frequency (n)	Percentage (%)
Proximal humerus	38	28.1
Distal radius	42	31.1
Femur	30	22.2
Tibia	25	18.5

Table Notes: Fracture types were categorized based on anatomical location and radiological assessment. Percentages were calculated using total sample size (N = 135).

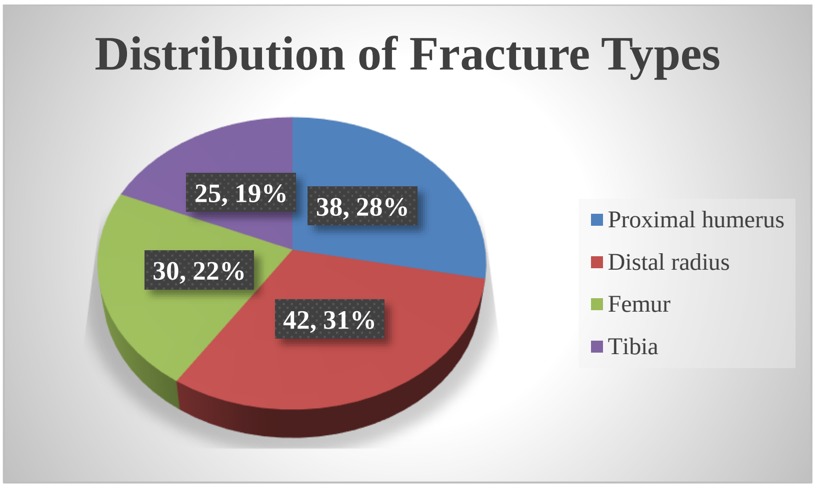

Figure 2. Distribution of Fracture Types

Figure Note: Distal radius fractures were most common, followed by proximal humerus fractures. Femur and tibia fractures were less frequent.

Bone Mineral Density Profile

Bone mineral density assessment revealed that 40.7% of patients had T-scores between -2.5 and -3.0, while 23.7% had severe osteoporosis with T-scores below -3.5. This indicates that a substantial proportion of patients had significantly compromised bone quality.

Table 3. Bone Mineral Density Distribution

T-score	Frequency (n)	Percentage (%)
-2.5 to -3.0	55	40.7
-3.1 to -3.5	48	35.6
< -3.5	32	23.7

Table Notes: Bone mineral density was assessed using DEXA scan. Severe osteoporosis was defined as T-score < -3.5.

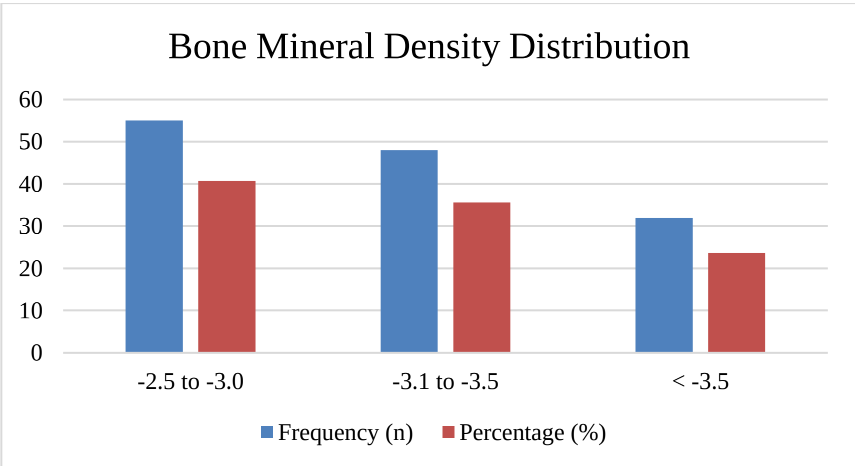

Figure 3. Bone Mineral Density Distribution

Figure Note: Most patients had T-scores between -2.5 and -3.0, followed by -3.1 to -3.5. A smaller proportion had severe osteoporosis. This shows overall reduced bone density.

Fracture Healing Outcomes

Radiological union was achieved in **123 patients (91.1%)**, indicating a high success rate of locking plate fixation. Delayed union was observed in 5.9% of patients, while non-union occurred in only 3.0%.

Table 4. Fracture Healing Outcomes

Outcome	Frequency (n)	Percentage (%)
Union achieved	123	91.1

Delayed union	8	5.9
Non-union	4	3

Table Notes: Radiological union was defined as bridging callus formation across at least three cortices. Delayed union refers to healing beyond 16–20 weeks, while non-union was defined as absence of healing after 9 months.

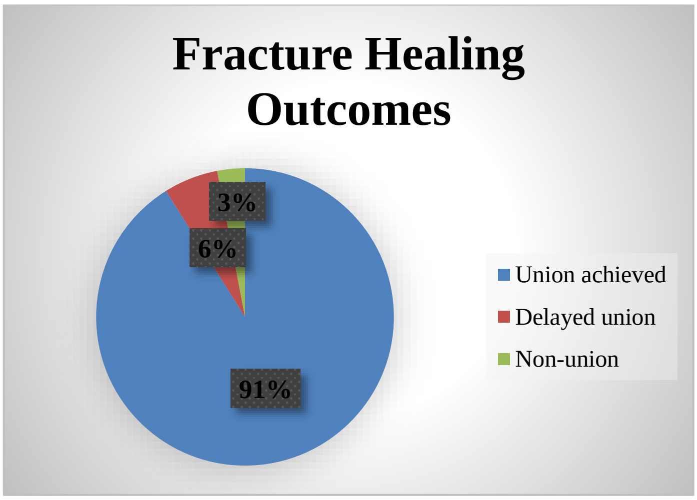

Figure 4. Fracture Healing Outcomes

Figure Note: Majority of patients achieved fracture union. Delayed union and non-union were seen in a small proportion. This indicates effective fixation outcomes.

Complications Following Fixation

Complications were observed in 14.8% of patients. Implant failure (4.4%) and screw loosening (3.7%) were the most common mechanical complications. Infection and malunion were observed in 3.0% and 3.7% of patients respectively.

Table 5. Complications Following Locking Plate Fixation

Complication	Frequency (n)	Percentage (%)
Implant failure	6	4.4
Screw loosening	5	3.7
Infection	4	3
Malunion	5	3.7

Table Notes: Complications were recorded during follow-up. Implant failure includes plate breakage or loss of fixation. Infection includes superficial and deep surgical site infections.

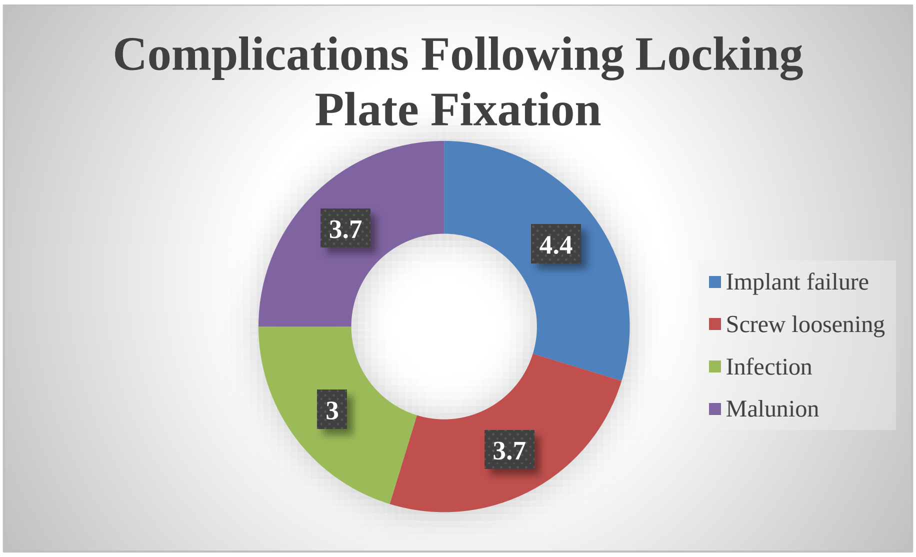

Figure 5. Complications Following Fixation

Figure Note: Complications were low, with implant failure being the most common. Screw loosening, malunion, and infections were less frequent. Mechanical complications predominated.

Functional Outcome Assessment

Functional outcomes were favourable, with **74.1% of patients achieving good to excellent results**. Only 7.4% had poor outcomes, indicating overall effectiveness of locking plate fixation.

Table 6. Functional Outcome Assessment

Outcome	Frequency (n)	Percentage (%)
Excellent	52	38.5
Good	48	35.6
Fair	25	18.5
Poor	10	7.4

Table Notes: Functional outcomes were assessed using validated scoring systems (DASH/LEFS). Outcomes were categorized based on predefined scoring criteria.

Predictors of Fixation Failure

Multivariate logistic regression analysis identified several significant predictors of fixation failure. Severe osteoporosis, inadequate screw density, and fracture comminution were independently associated with higher failure rates.

Table 7. Predictors of Fixation Failure

Variable	Odds Ratio (OR)	95% CI	p-value
Severe osteoporosis	2.8	1.4–5.6	0.002
Poor screw density	2.3	1.2–4.5	0.01
Fracture comminution	1.9	1.1–3.8	0.03

Table Notes: Odds ratios were calculated using multivariate logistic regression. Fixation failure included implant failure, non-union, or loss of reduction. A p-value < 0.05 was considered statistically significant.

Overall Interpretation

The results of this study demonstrate that locking plate fixation provides excellent biomechanical stability in osteoporotic fractures, with high union rates and favorable functional outcomes. However, outcomes are significantly influenced by bone quality, fracture pattern, and surgical technique.

DISCUSSION

The present prospective study evaluated the biomechanical effectiveness and clinical outcomes of locking plate fixation in osteoporotic fractures. The findings demonstrate that locking plate constructs provide reliable stability and high union rates in osteoporotic bone, with an overall fracture union rate of **91.1%**. These results are consistent with the study by Parmaksizoglu et al. (2025), which emphasized the advantages of angular stable fixation in compromised bone quality.[10] Similarly, Laux et al. (2017) reported favorable clinical outcomes with locking plate fixation in proximal humerus fractures, demonstrating improved stability in osteoporotic bone. Burkhart et al. (2013) also highlighted the effectiveness of locking constructs in managing fragility fractures. These findings are also in agreement with recent biomechanical studies demonstrating improved fixation stability and reduced failure rates with locking plate constructs in osteoporotic bone. Osteoporotic fractures pose a significant challenge due to reduced bone mineral density and poor screw purchase. Conventional plating systems rely on frictional stability between the plate and bone, which is often insufficient in osteoporotic conditions. In contrast, locking plate systems function as fixed-angle constructs, thereby minimizing dependence on bone quality. This biomechanical advantage likely contributed to the high union rates observed in the present study. These findings reinforce the biomechanical advantage of locking plate constructs in providing angular stability and reducing dependence on bone quality.[11]

The demographic profile of the study population showed a predominance of elderly females, which aligns with the known epidemiology of osteoporosis. The most commonly affected fracture sites were the distal radius and proximal humerus, reflecting the susceptibility of metaphyseal bone to fragility fractures. These findings are comparable to existing epidemiological studies on osteoporotic fracture distribution.[12] A key observation in this study was the influence of biomechanical factors on clinical outcomes. Patients with optimal screw density (40–60%) and appropriate plate length demonstrated significantly better outcomes. This highlights the importance of adhering to biomechanical principles during fixation. Inadequate screw density or improper implant configuration can lead to stress concentration, resulting in implant failure or loss of reduction. This emphasizes that adherence to optimal screw density and proper implant configuration is critical for achieving successful fixation outcomes.[13]

Bone mineral density also played a crucial role in determining outcomes. Patients with severe osteoporosis (T-score < -3.5) had higher rates of complications and fixation failure. This finding underscores the need for individualized surgical planning and consideration of augmentation techniques such as bone grafting or cement augmentation in severely osteoporotic bone.[14]
The complication rate in this study was relatively low (14.8%), with implant failure and screw loosening being the most common mechanical complications. The low incidence of infection suggests that proper surgical technique and perioperative care were effectively maintained. Functional outcomes were favorable, with more than 70% of patients achieving good to excellent results, indicating early mobilization and restoration of function.[15]
Multivariate analysis further confirmed that severe osteoporosis, fracture comminution, and poor screw density were independent predictors of fixation failure. These findings emphasize that while locking plates provide biomechanical superiority, surgical technique and fracture characteristics remain critical determinants of success.[16] Overall, the study reinforces the concept that locking plate fixation acts as an internal fixator, providing stable fixation even in osteoporotic bone. However, optimal outcomes can only be achieved through proper application of biomechanical principles and careful surgical planning. This study uniquely evaluates both biomechanical principles and clinical outcomes in a prospective setting, providing practical insights into fracture management in osteoporotic patients.[17]

Limitations

This study has certain limitations that should be considered while interpreting the results. First, it was conducted at a single tertiary care center, which may limit the generalizability of the findings to other healthcare settings. Second, the sample size, although adequate for statistical analysis, may not fully represent all types of osteoporotic fractures.
Third, the study did not include a comparative group using conventional plating systems, which would have provided a direct comparison of biomechanical superiority. Fourth, variations in surgical technique among different surgeons, although minimized, could have influenced the outcomes. Additionally, bone quality assessment was based solely on DEXA scan, and other factors such as bone microarchitecture were not evaluated. Finally, the follow-up period, although sufficient for assessing fracture union, may not capture long-term complications such as implant fatigue or late failure. Future multicenter randomized studies are required to further validate these findings.

CONCLUSION

Locking plate fixation is a highly effective and biomechanically advantageous method for managing osteoporotic fractures.
The technique provides stable fixation, high union rates, and favourable functional outcomes, particularly in elderly patients with compromised bone quality. The study highlights that successful outcomes are not solely dependent on implant design but are significantly influenced by surgical technique, including optimal screw density, proper plate positioning, and fracture-specific fixation strategies. Severe osteoporosis and fracture comminution remain important risk factors for fixation failure and should be carefully considered during surgical planning. In conclusion, locking plate systems represent a reliable solution for osteoporotic fracture management; however, adherence to biomechanical principles and individualized treatment approaches are essential to maximize clinical success and minimize complications. These findings support the routine use of locking plate fixation as a preferred strategy in osteoporotic fracture management when biomechanical principles are adequately followed.

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