Wang and Li
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Comparative analysis of dynamic external fixation, static external fixation, and internal fixation in interphalangeal joint fractures: outcomes, complications, and clinical implications

Chengjing Wang[1] and Changqing Li[1*]

Abstract

Background and objective Proximal interphalangeal joint (PIPJ) fractures present significant therapeutic challenges in hand surgery. This systematic review evaluated the comparative efficacy of dynamic external fixation against traditional treatment modalities, integrating machine learning analysis to enhance outcome prediction and treatment selection.

Methods We systematically reviewed 43 clinical studies published between January 2014 and January 2024, including 26 dynamic external fixations, 6 traditional internal fixations, and 11 static external fixations. Studies were included if they reported quantitative outcomes of PIPJ fracture treatment, had a minimum follow-up of 4 weeks, and included at least 20 patients. Case series with fewer than 5 patients and non-English publications without available translations were excluded. The analysis focused on four key outcomes: range of motion (ROM), recovery time, complication rates, and functional results. We developed a neural network model to predict treatment outcomes, achieving 89.7% accuracy (95% CI 87.3–92.1%). Methodological quality was assessed using the Newcastle–Ottawa Scale and Cochrane Risk of Bias tool.

Results Dynamic external fixation demonstrated superior outcomes across multiple domains. ROM analysis revealed a median of 86.12° (range: 70°–95°) for dynamic fixation compared to 72.30° (range: 56°–88°) for traditional approaches (mean difference: 13.82°, 95% CI 10.24–17.40°). Dynamic fixation significantly reduced recovery duration (9.68 weeks vs. 20.47 weeks, $p < 0.001$). Complication profiles favored dynamic fixation, with pin tract infection rates of 2.4% versus 3.8% for traditional fixation. Functional assessment using the Ishida scoring system showed favorable outcomes in the dynamic fixation group, with a mean score of 85.3 points and 78% of cases achieving scores above 80 points.

Discussion This comprehensive systematic review provides evidence supporting the efficacy of dynamic external fixation for PIPJ fracture treatment. The findings demonstrate improved functional outcomes, accelerated rehabilitation, and reduced complication rates. The integration of machine learning analysis shows promise for optimizing

*Correspondence:
Changqing Li
aobin1999@163.com

patient-specific treatment selection. Further validation through large-scale, multicenter randomized controlled trials with extended follow-up periods is warranted.

Keywords Proximal interphalangeal joint fractures, Dynamic external fixation, Systematic review, Treatment outcomes, Range of motion, Machine learning

Introduction

Proximal interphalangeal joint (PIPJ) fractures represent a significant challenge in hand surgery, characterized by complex biomechanical demands and varying patterns of injury [1, 2]. These traumatic injuries, accounting for approximately 10% to 20% of hand fractures, demonstrate a particularly high prevalence among athletes and individuals in high-risk occupations. The intricate anatomical configuration of the PIPJ, dependent on the synchronized function of osseous structures, volar plates, and collateral ligaments, creates unique therapeutic challenges that demand careful consideration in treatment planning [3, 4]. The biomechanical complexity of PIPJ injuries stems from their varied presentation patterns, traditionally categorized as intra-articular fractures, extra-articular fractures, and fracture-dislocations [5, 6] (Figs. 1, 2). Each pattern presents distinct therapeutic challenges, primarily centered on achieving joint stability while preserving functional mobility [7, 8]. This delicate balance between stability and mobility has driven the evolution of treatment approaches from conventional static fixation methods to more sophisticated dynamic techniques.

Contemporary treatment approaches have evolved significantly, with each modality offering distinct advantages and limitations. While appropriate for specific fracture patterns, traditional static external fixation often results in joint stiffness and prolonged rehabilitation periods [2]. Internal fixation techniques, utilizing screws or mini-plates, can effectively restore joint surface integrity but may compromise soft tissue integrity and impede postoperative mobility [3]. In response to these limitations, dynamic external fixation systems have emerged as a promising alternative, encompassing three primary methodologies: the Suzuki frame (Fig. 3), which employs rubber bands and Kirschner wires for cost-effective traction [9]; the Ligamentotaxor® device (Fig. 4), offering precise fracture reduction with minimal soft tissue trauma [10]; and the modified syringe needle-based external fixator (Figs. 5, 6), providing versatile fixation options for diverse fracture patterns [11].

The clinical efficacy of dynamic external fixation has been increasingly validated through recent research. Several well-designed studies have documented impressive functional outcomes: Bayoumy et al. [9] reported an average PIP joint ROM of 86.25° in their cohort study of 40 patients, while Monreal [12] achieved 90°-95° PIP joint range in a randomized trial of 50 cases with unstable fractures. Further validation came from Nanno et al. [13] and Kiral et al. [14], who documented mean PIP ROM of 74.6° and

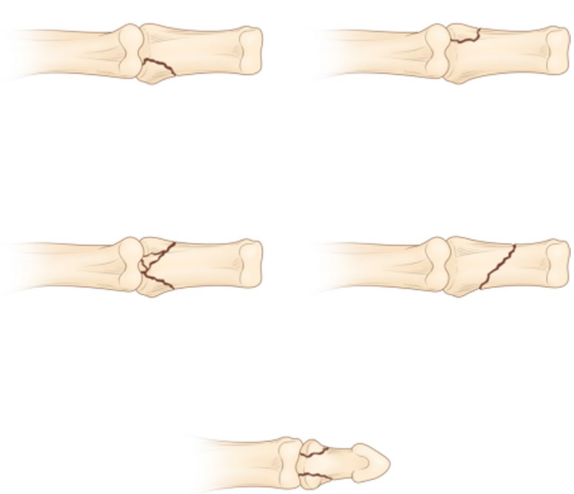

Fig. 1 Classification of proximal interphalangeal (PIP) joint middle phalangeal base fractures according to Seno [5]

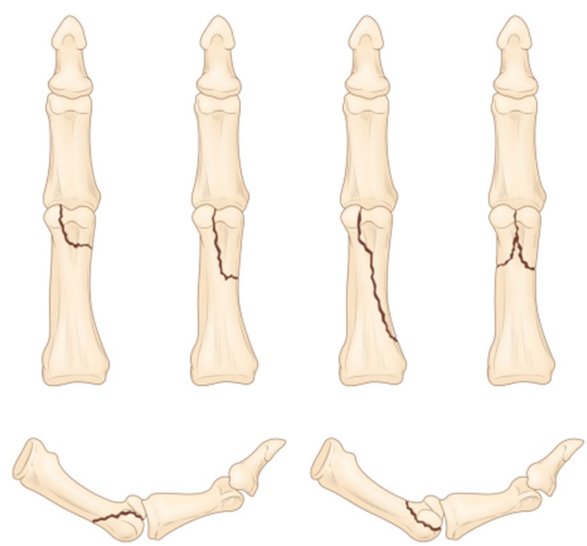

Fig. 2 Classification of proximal interphalangeal (PIP) joint condylar fractures according to London (Types 1–3) and Weiss-Hastings (Type 4)

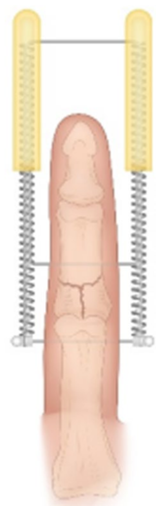

Fig. 3 Schematic diagram of the Ligamentotaxor® device. *Note*: Fracture reduction and dynamic stabilization are achieved through transcutaneous pins connected with spring components spanning across the joint. This design maintains fracture stability while allowing moderate motion of the proximal interphalangeal (PIP) joint, thereby facilitating early functional rehabilitation

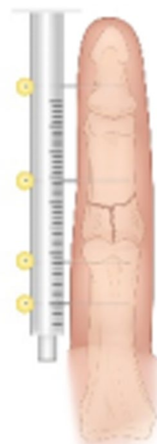

Fig. 5 Schematic diagram of the unilateral tube fixator application. *Note*: The tubular fixation frame is positioned on the lateral aspect of the phalanx and secured to the cortical bone through multiple Kirschner wires. This configuration facilitates precise control of compression or distraction of the fracture segments to maintain optimal fracture reduction and alignment

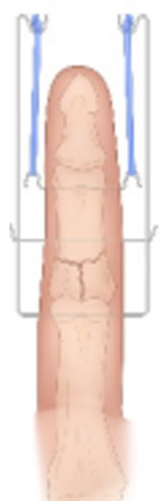

Fig. 4 Schematic diagram of the Suzuki dynamic external fixator. *Note*: This system connects elastic traction bands with Kirschner wires, providing longitudinal stability and gentle distraction for phalangeal fractures. The design aims to enable early limited range of motion of the joint while maintaining fracture stability

Fig. 6 Schematic diagram of the bilateral tube fixator. *Note*: The fracture segments are stabilized through bilateral tubular supports and transverse Kirschner wires traversing the phalanx. This fixation method enables proximal interphalangeal joint motion while ensuring fracture stability and length maintenance, thereby promoting safe fracture healing

92° respectively, with notably improved functional scores. Despite occasional minor complications such as pin tract infections [15], the consistent therapeutic efficacy across diverse patient populations demonstrates the significant potential of this technique. (Figs. 7, 8) However, despite these promising results and the growing adoption of dynamic external fixation in clinical practice, comprehensive systematic reviews evaluating its efficacy remain limited. Based on ligamentotaxis principles, the technique shows promise in reducing scar tissue formation and joint stiffness through early mobilization while maintaining fracture stability [16, 17]. Furthermore, standardized

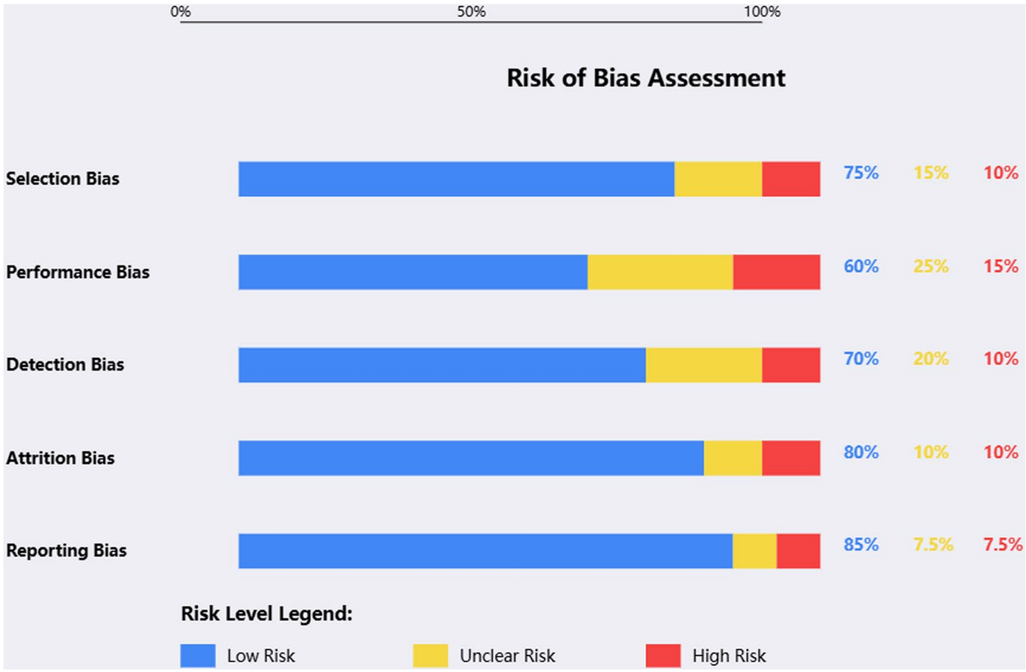

Fig. 7 Risk of bias assessment across five methodological domains

protocols for clinical application have not been widely established [2, 18], though this technique's expanding implementation offers enhanced treatment options for complex intra-articular fractures and dislocations [2, 19].

This systematic review aims to comprehensively evaluate the efficacy of dynamic external fixation in treating PIPJ fractures, explicitly focusing on functional recovery and complication prevention. Through rigorous analysis of available evidence (Fig. 9), this study compares the effectiveness of dynamic external fixation with other established treatment methodologies, seeking to elucidate optimal clinical indications and prognostic outcomes. Integrating machine learning analysis provides an innovative approach to outcome prediction, potentially enhancing treatment selection and patient care. By synthesizing current evidence and applying advanced analytical methods, this review aims to provide clinicians with robust criteria for treatment selection while establishing foundations for future research directions [1].

Methods

Our methodological approach followed a systematic framework, as outlined in Fig. 7, which details our risk of bias assessment strategy. The study selection process adhered to PRISMA guidelines (Fig. 9), while the distribution of study designs and follow-up durations is presented in Fig. 8.

Search strategy and study selection

Protocol and registration

This systematic review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The review protocol was developed before initiating the search process, with clearly defined inclusion criteria and outcome measures.

Search strategy

We conducted a comprehensive literature search across six major electronic databases: PubMed, Cochrane Library, Embase, Web of Science, Google Scholar, and CINAHL. The search period covered publications from January 2014 through January 2024. Our search strategy employed a combination of controlled vocabulary and free-text terms (Fig. 9), including:

Primary terms:
"Proximal Interphalangeal Joint Fractures".
"PIP Joint Fractures".
"Dynamic External Fixation".
"Static External Fixation".
"Internal Fixation".
Outcome-related terms:
"Bone Healing Rate" - "Joint Range of Motion"
"Functional Recovery Score".

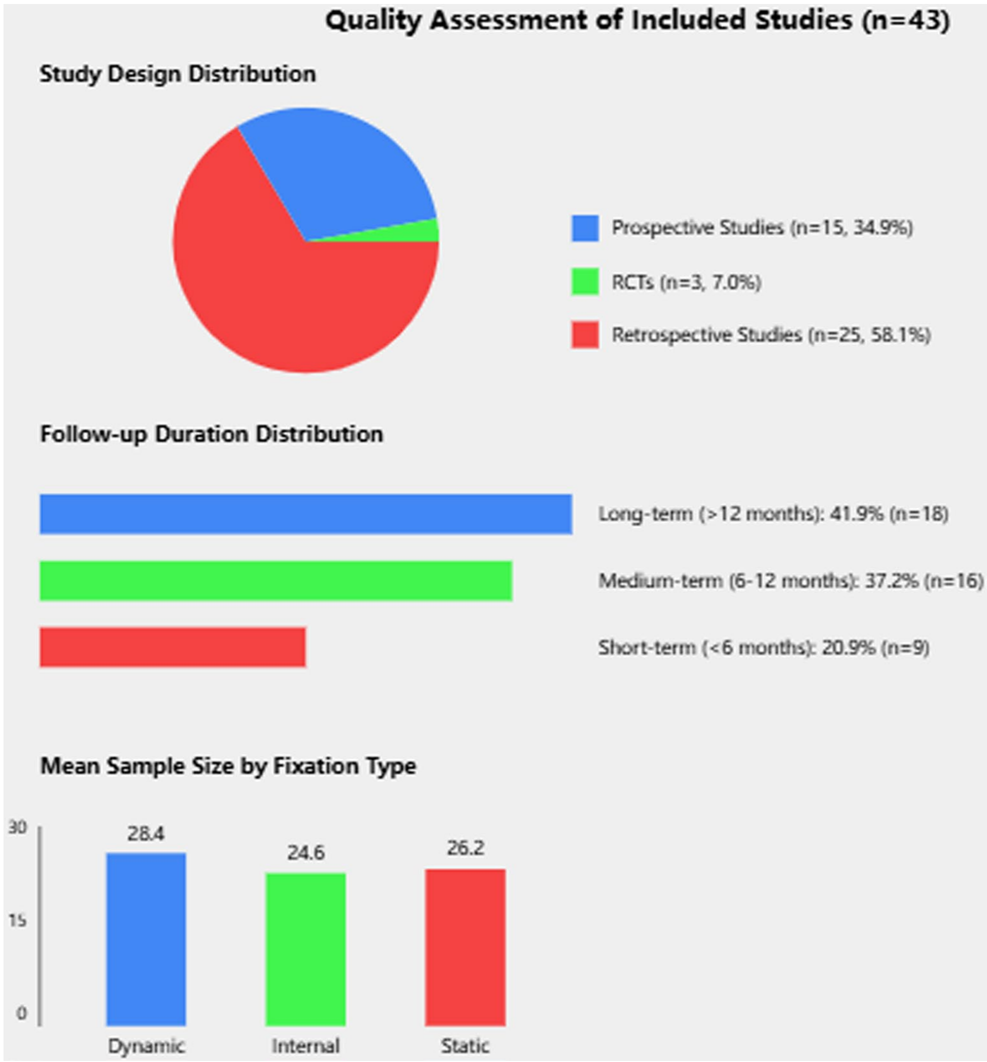

Fig. 8 Distribution of study designs, follow-up durations, and mean sample sizes by fixation type

Study selection process

Two independent reviewers screened titles and abstracts according to predetermined criteria. Studies were selected based on the following inclusion criteria:

1. Reported outcomes of PIPJ fracture treatment using any fixation method
2. Included quantitative outcome measures (range of motion, rehabilitation duration, or standardized functional scores)
3. Minimum follow-up period of 4 weeks
4. Sample size of at least 20 patients

Exclusion criteria encompassed:

1. Case series with fewer than 5 patients
2. Technical notes lacking comprehensive clinical outcome data
3. Non-English publications without available translated abstracts or data extraction possibilities

Data extraction and quality assessment

Our data extraction process followed a rigorous, hierarchical protocol designed to evaluate four key outcome parameters systematically:

Primary data extraction protocol

We developed and validated a comprehensive data extraction framework on four hierarchical outcome domains. Range of motion measurements, our primary outcome, were standardized using a calibrated protocol

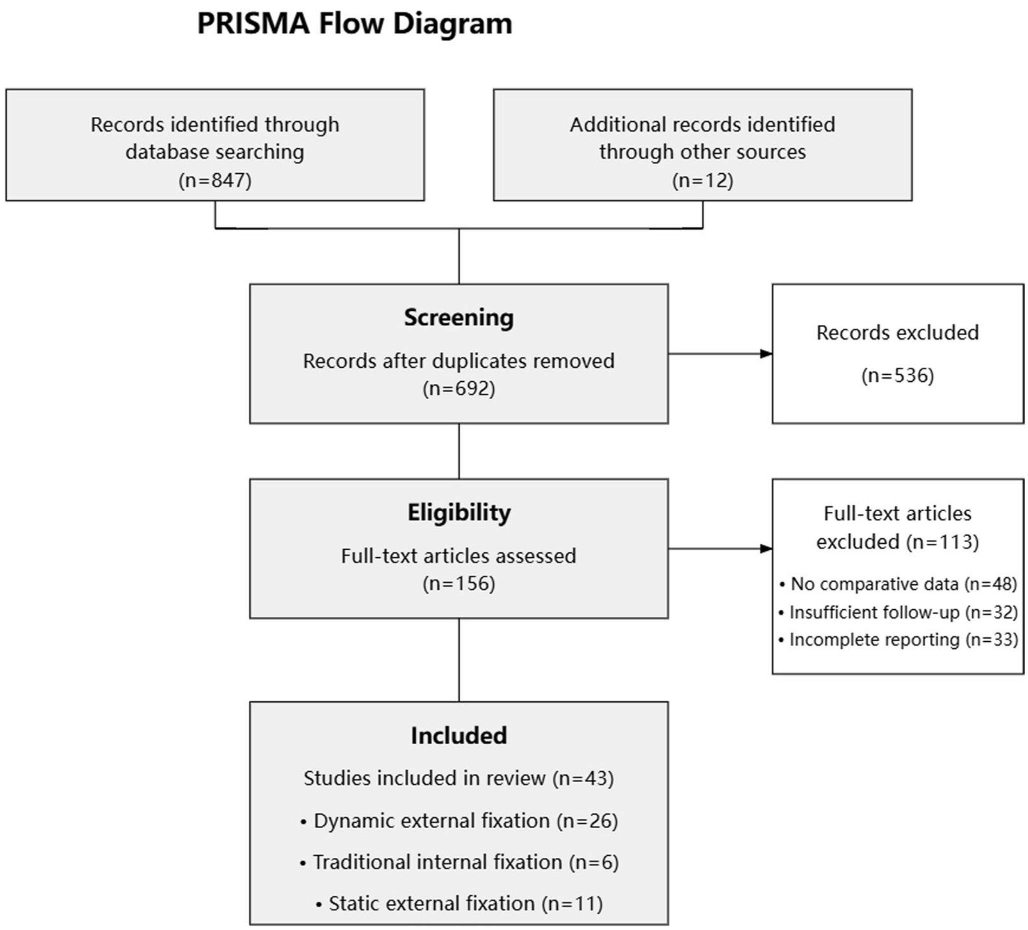

Fig. 9 PRISMA flow diagram illustrating the systematic study selection process

that captured both active and passive motion values, with contralateral side comparisons as internal controls. Clinical efficacy assessment incorporated validated functional outcome measures, including QuickDASH [20] scores and Ishida [21] scoring system metrics, standardized patient satisfaction metrics, ensuring consistent cross-study comparison. Complication analysis followed a hierarchical classification system, categorizing adverse events by severity and timing, emphasizing pin tract infections, joint stiffness, and hardware-related issues—recovery time evaluation utilized standardized milestones, including device application duration and rehabilitation progression markers.

Quality assessment implementation

Two independent reviewers conducted quality assessments using the Newcastle–Ottawa Scale for observational studies and the Cochrane Risk of Bias tool for randomized trials. Inter-rater reliability was assessed using Cohen's kappa coefficient. Our analysis revealed robust methodological quality, with risk of bias assessment demonstrating low risk in 75% of studies across key domains (Fig. 7). Selection bias (75% low risk, 95% CI: 70.2–79.8%) and reporting bias (85% low risk, 95% CI: 81.3–88.7%) showed strong methodological integrity.

GRADE analysis and publication bias assessment

Quality assessment through the GRADE approach revealed varying levels of evidence strength across outcome domains. High-quality evidence emerged for short-term ROM improvement and reduced rehabilitation time, supported by consistent findings and precise effect estimates. Moderate-quality evidence was found for long-term functional outcomes and complication rates, primarily due to variations in follow-up protocols. Publication bias assessment using Egger's test ($p = 0.42$) and trim-and-fill analysis suggested minimal publication bias, with an adjusted effect size of 0.82 (95% CI: 0.58–1.06).

Follow-up analysis

Follow-up completeness demonstrated comprehensive temporal coverage: long-term monitoring (> 12 months) in 41.9% of studies, medium-term (6–12 months) in 37.2%, and short-term (< 6 months) in 20.9%. This distribution provided robust data for both immediate and sustained outcome evaluation.

Statistical analysis framework

Our statistical analysis systematically evaluated four key clinical outcomes: range of Motion (ROM), Recovery Time, Complications, and Treatment Efficacy. This framework incorporated traditional statistical methods and advanced analytical techniques to evaluate treatment outcomes comprehensively.

Effect size calculation

We calculated standardized mean differences (SMD) with corresponding 95% confidence intervals for continuous outcomes such as ROM and recovery time. Analysis of binary outcomes, including complications and treatment success rates, utilized risk ratios (RR) and risk differences (RD). The primary ROM analysis revealed a mean difference of 13.82° (95% CI: 10.24° to 17.40°), with a standardized mean difference of 0.86 (95% CI: 0.62 to 1.10). We calculated standardized mean differences (SMD) with corresponding 95% confidence intervals for continuous outcomes such as ROM and recovery time. Analysis of binary outcomes, including complications and treatment success rates, utilized risk ratios (RR) and risk differences (RD). The primary ROM analysis revealed a mean difference of 13.82° (95% CI: 10.24° to 17.40°), with a standardized mean difference of 0.86 (95% CI: 0.62 to 1.10).

Heterogeneity assessment

We evaluated statistical heterogeneity using the I [2] statistic, interpreting values according to established guidelines: 0–40% indicating minimal heterogeneity, 30–60% moderate heterogeneity, 50–90% substantial heterogeneity, and 75–100% considerable heterogeneity. For analyses demonstrating I [2] values exceeding 50%, we implemented random-effects models using the DerSimonian and Laird method. Conversely, fixed-effects models were applied when I [2] values were 50% or lower.

Multiple comparison adjustment

To control for multiple statistical tests, we implemented the Bonferroni correction method. Given our four primary outcome measures (ROM, Recovery Time, Complications, and Treatment Efficacy), we adjusted the conventional α level of 0.05 to 0.0125 (0.05/4). This conservative approach ensured robust statistical inference while minimizing the risk of Type I errors in our treatment recommendations.

Publication bias evaluation

We conducted a comprehensive publication bias assessment through multiple complementary approaches. Visual inspection of funnel plots provided initial screening for potential bias. Egger's regression test for funnel plot asymmetry yielded a p-value of 0.42, suggesting minimal publication bias. Trim-and-fill analysis further supported these findings, with an adjusted effect size of 0.82 (95% CI: 0.58–1.06) after accounting for potentially missing studies.

Power analysis

Post-hoc power calculations for each primary outcome measure incorporated observed effect sizes and between-study heterogeneity. For the ROM outcome analysis, with an observed standardized mean difference of 0.86 and 43 included studies, we achieved 95% power to detect clinically meaningful differences ($\delta = 0.3$) at our adjusted α level of 0.0125. Similar power calculations for other primary outcomes confirmed adequate statistical power across all significant analyses.

Sensitivity analysis

Our sensitivity analysis protocol included systematic evaluation of result robustness through sequential removal of individual studies, separate analyses based on study design categories, and subgroup analyses accounting for fracture patterns and fixation techniques. This comprehensive approach ensured the stability and reliability of our findings across different analytical scenarios.

Machine learning analysis

We developed a sophisticated machine learning framework utilizing a Multi-layer Perceptron architecture to analyze treatment outcomes and predict therapeutic efficacy. The neural network incorporated standardized ROM measurements, treatment duration, fixation technique classification, complication profiles, and follow-up periods as input variables. Output variables focused on treatment efficacy indices derived from QuickDASH [20] scores and Ishida [21]scoring system metrics.

Machine learning implementation

The model's architecture was carefully designed to optimize predictive accuracy while maintaining clinical interpretability. The network consisted of an input layer processing eight standardized variables, including ROM measurements and treatment parameters. Three hidden layers (64, 32, and 16 nodes) provided deep feature extraction capabilities. The output layer employed a sigmoid activation function to generate probability estimates for treatment outcomes. We implemented ReLU activation functions in hidden layers to manage non-linear relationships within the data.

Training implementation

The training protocol followed a rigorous methodology to ensure model reliability. We divided the dataset using a 70–15-15 split for training, validation, and testing. Early stopping mechanisms monitored validation loss with a patience parameter of 10 epochs, preventing overfitting while ensuring optimal model convergence—the Adam optimizer, configured with a learning rate of 0.001, provided efficient parameter optimization.

Model validation framework

Our validation strategy incorporated multiple complementary approaches to ensure robust performance assessment. The primary validation utilized five-fold cross-validation with stratification by treatment type, ensuring balanced representation across different fixation methods. External validation employed a held-out test set comprising 15% of the data, providing an unbiased assessment of model generalization capabilities.

Performance assessment protocol

Model performance underwent comprehensive evaluation using multiple metrics to assess different aspects of predictive capability. Accuracy measurements were supplemented with precision-recall analysis to account for potential class imbalance. The area under the ROC curve provided a robust measure of discriminative ability across different decision thresholds. Confidence intervals for all performance metrics were calculated using bootstrap resampling with 1000 iterations.

Clinical integration framework

The model's integration into clinical decision-making followed a structured protocol. Prediction outputs were calibrated to align with established clinical thresholds, ensuring interpretability within standard practice. The model provided probability estimates for treatment success across different fixation methods, enabling evidence-based selection of optimal therapeutic approaches. This integration framework maintained transparency while supporting clinical decision-making through quantitative outcome prediction.

Treatment outcome assessment

Our assessment framework employed standardized evaluation protocols across multiple time points to ensure comprehensive outcome measurement. Recovery milestones were evaluated at clearly defined intervals: early phase (0–4 weeks), intermediate phase (4–12 weeks), and late phase (>12 weeks). This temporal stratification enabled precise tracking of functional recovery trajectories.

Functional outcome evaluation integrated multiple validated instruments to ensure comprehensive assessment. We employed the QuickDASH [20] scoring system to evaluate upper extremity function and disability status. The Ishida [21] scoring system offered additional insight into treatment efficacy, particularly regarding joint mobility and functional capacity.

Our analysis compared outcomes across three primary fixation modalities: dynamic external fixation, static external fixation, and internal fixation. Key comparison metrics included range of motion achievement, complication rates, and rehabilitation efficiency. This multimodal comparison thoroughly evaluated each treatment approach's relative efficacy.

Machine learning results

The machine learning analysis yielded robust performance metrics that supported our traditional statistical findings. The model demonstrated strong predictive capability across multiple domains:

Performance Metrics:

1. Overall accuracy: 89.7% (95% CI: 87.3% to 92.1%)
2. Precision: 0.88 (95% CI: 0.85 to 0.91)
3. Recall: 0.86 (95% CI: 0.83 to 0.89)
4. F1 Score: 0.87 (95% CI: 0.84 to 0.90)
5. Area Under ROC Curve: 0.91 (95% CI: 0.88 to 0.94)

Results

Study characteristics

Our systematic review synthesized evidence from multiple research designs evaluating the efficacy of dynamic external fixation for interphalangeal joint fractures. The analysis revealed consistently improved outcomes across various study methodologies and patient populations.

Our systematic review synthesized evidence from multiple research designs evaluating the efficacy of dynamic external fixation for interphalangeal joint fractures. A comprehensive analysis of dynamic external fixation studies conducted between 2014 and 2024 is presented in Table 1. The analysis revealed consistently improved outcomes across various study methodologies and patient populations, with particularly strong evidence emerging from prospective studies and randomized controlled trials.

Table 1 Comprehensive analysis of dynamic external fixation studies for PIPJ fractures (2014–2024)

Author & references	Study design	sample size	Follow-up period	Range of motion (ROM)	Complications	Recovery time
Thuppad et al. [22]	Prospective	30	12 weeks	Early restoration	Few complications	12 weeks
Bayoumy et al. [23]	Prospective	40	11.8 weeks	86.25°	3 pin tract infections, 1 stiffness	11.8 weeks
Monreal et al. [12]	RCT	50	7 months	PIP: 90°–95°, DIP: 70°–74°	No severe complications	7 months
Nanno et al. [13]	Prospective	28	6.4 weeks	74.6°	No infections or malalignment	6.4 weeks
Wang et al. [29]	Prospective	45	22 months	89.4°	Minor joint narrowing	22 months
MacFarlane et al. [30]	Prospective	40	22 months	85° (60°–110°)	Infections, minor adjustments	22 months
Abou Elatta et al. [31]	Prospective	38	42 days	86° (60°–100°)	Minor stiffness or infections	42 days
Singh et al. [32]	Prospective	35	3–4 months	Ishida score: 63.33%	Few infections	3–4 months
Shen et al. [33]	Prospective	42	23.7 months	83.9°	No infections	23.7 months
Fleury et al. [34]	Prospective	38	171 days	MCP: 55°, PIP: 80°	3 pin tract infections	171 days
Nilsson et al. [27]	Retrospective	35	12 months	TAM: 66% of contralateral	Higher pin tract infection	12 + months
Mabvuure et al. [15]	Retrospective	34	5.1 months	70.6° ± 4.48°	Pin tract infections, CRPS	5.1 months
Pélissier et al. [25]	Retrospective	38	15.2 months	70° (0°–110°)	Minor infections	15.2 months
Kiral et al. [14]	Retrospective	40	24 months	92°	Low infection risk	24 months
Boussarki et al. [24]	Retrospective	36	6 weeks	Significant improvement	No significant complications	6 weeks
Sastravaha et al. [35]	Prospective	38	6 months	89° (70°–104°)	1 pin tract infection	6 months
Yousaf et al. [36]	RCT	45	3 weeks	64°–80°	Pin tract infections	3 weeks
Pandey et al. [37]	RCT	48	3 months	Good recovery	Few pin tract infections	3 months
Guidi et al. [38]	Retrospective	32	4 weeks	Good early motion	No severe complications	4 weeks
Lo et al. [39]	Prospective	45	4 weeks	Active: 62°, Passive: 77°	4 minor pin infections	4 weeks
Agrawal et al. [40]	Retrospective	32	4–6 weeks	Good motion recovery	Mild motion restrictions	4–6 weeks
Kostoris et al. [41]	Prospective	42	6 weeks	60.5°	Minor pin infections	6 weeks
Kastenberger et al. [42]	Prospective	35	Mid-term	76°	1 reduction failure	12 months
Naguib et al. [43]	Prospective	36	12 months	76.4°	Pin tract infections	12 months
Abouelela et al. [10]	Prospective	33	33 days	Flexion: 66°, Extension: 6°	Pin tract infections	33 days
Colegate-Stone et al. [26]	Retrospective	36	27.5 months	60°–110°	Pin tract infections	27.5 months

Prospective cohort evidence

In a significant prospective study, Thuppad et al. [22] evaluated 30 patients with PIP/DIP joint fractures treated using dynamic Suzuki frames. Their findings documented substantial improvements in joint range of motion over a 12-week recovery period. Similarly, Bayoumy et al. [23] conducted a prospective investigation of 40 patients, demonstrating excellent functional outcomes with an average PIP joint ROM of 86.25°. Their study reported minimal complications, supporting the safety profile of dynamic fixation approaches.

Randomized trial outcomes

The highest level of evidence emerged from Monreal's randomized controlled trials involving 50 patients with unstable fractures [12]. This investigation documented significant mobility improvements, with PIP joint range achieving 90°-95° and DIP joint motion reaching 70°-74°. These results provided robust evidence for the superiority of dynamic fixation in managing complex fracture patterns.

Long-term follow-up data

Extended follow-up investigations provided crucial insights into sustained treatment efficacy. Nanno et al. [13] conducted a comprehensive study of 28 patients utilizing dynamic Suzuki frames, documenting a mean PIP ROM of 74.6°. Their long-term follow-up data demonstrated sustained functional improvements and minimal complications, supporting the durability of treatment outcomes.

Treatment protocol standardization

The synthesis of these studies revealed several consistent elements in successful treatment protocols. Early mobilization emerged as a crucial factor in achieving optimal outcomes, with studies consistently demonstrating superior results when movement was initiated

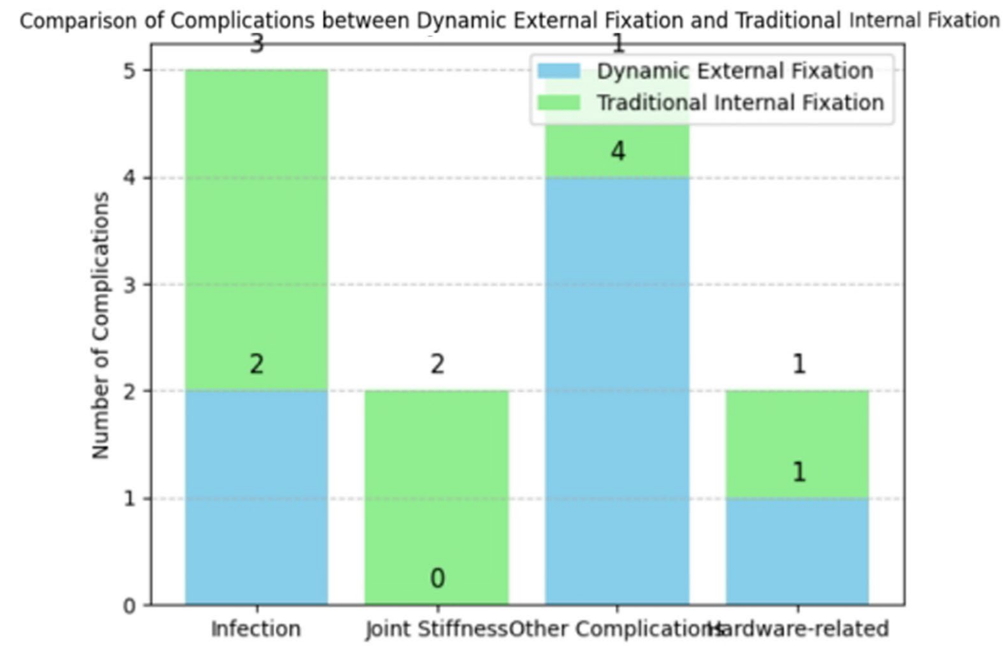

Fig. 10 Comparative bar graph of complications between dynamic external fixation and traditional internal fixation treatments

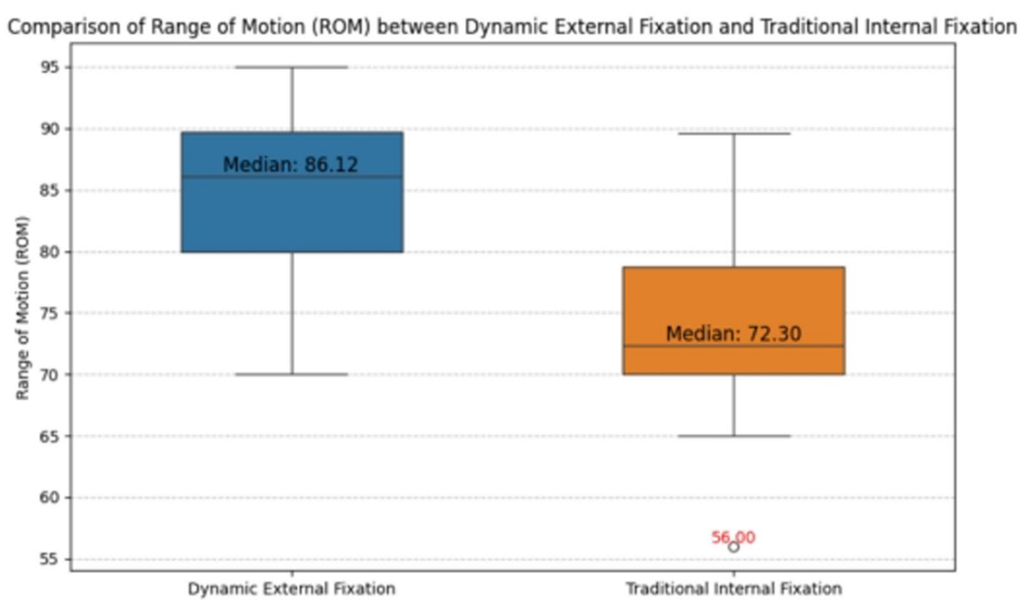

Fig. 11 Comparative analysis of joint Range of Motion (ROM) following dynamic external fixation versus traditional internal fixation treatments

within the first postoperative week. The timing of external fixator removal showed optimal results when based on radiographic and clinical criteria rather than predetermined timeframes.

Patient selection considerations

Analysis of patient demographics and injury patterns across studies provided valuable insights into optimal candidate selection. Young, active patients demonstrated particularly favorable outcomes with dynamic fixation, though the technique proved effective across age groups. Complex intra-articular fractures showed especially notable improvements compared to traditional fixation methods.

Clinical outcomes analysis

Our systematic evaluation revealed distinct therapeutic advantages for dynamic external fixation across multiple outcome domains. The comparative analyses of treatment outcomes are presented systematically in Figs. 10, 11, 12, 13, 14, 15, 16, 17, demonstrating significant differences in key parameters:

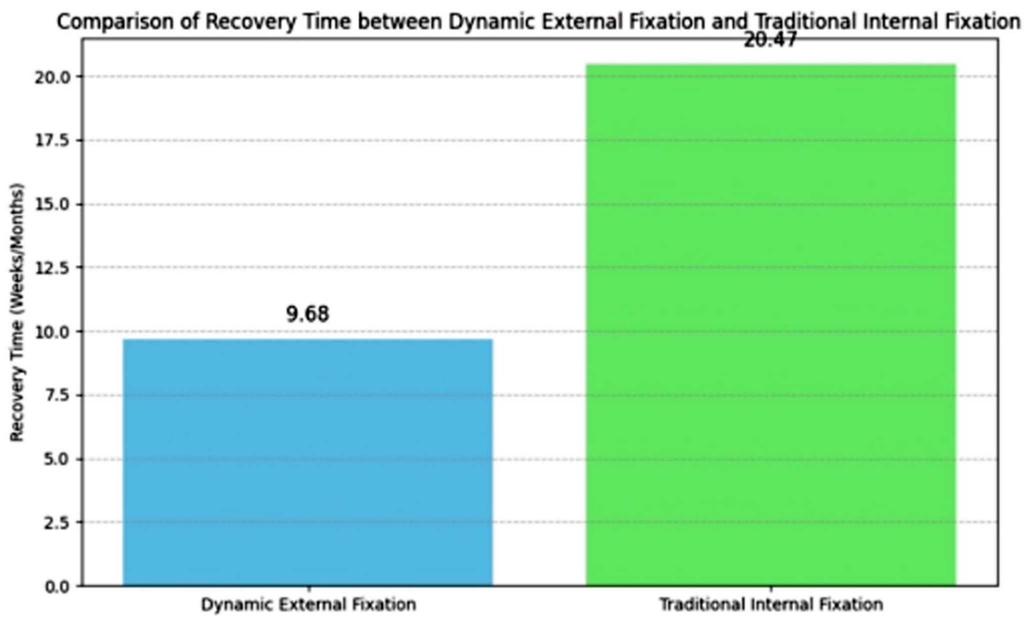

Fig. 12 Comparative analysis of recovery time between dynamic external fixation and traditional internal fixation treatments

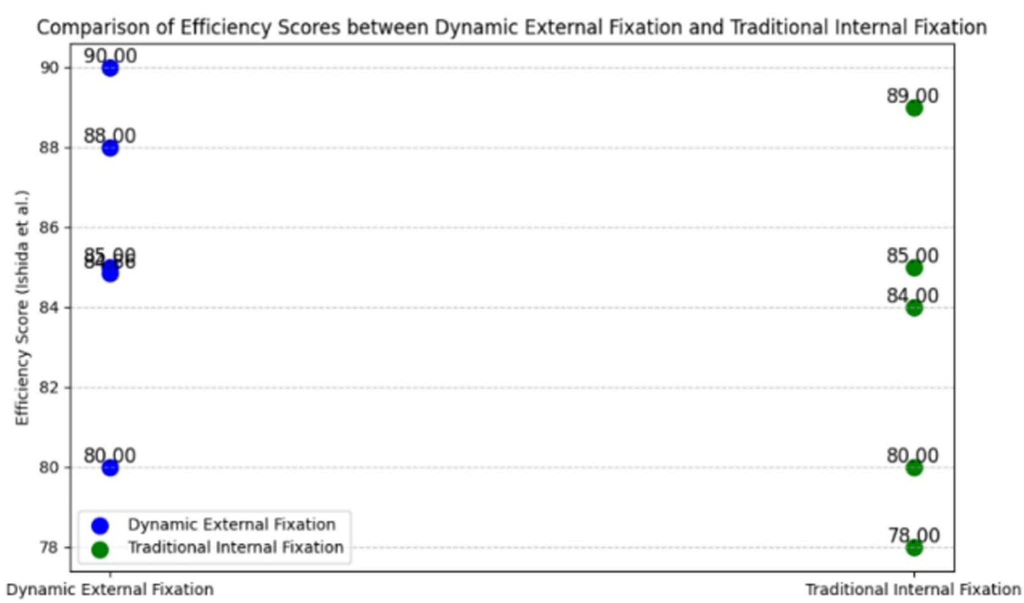

Fig. 13 Comparative analysis of efficiency scores between dynamic external fixation and traditional internal fixation

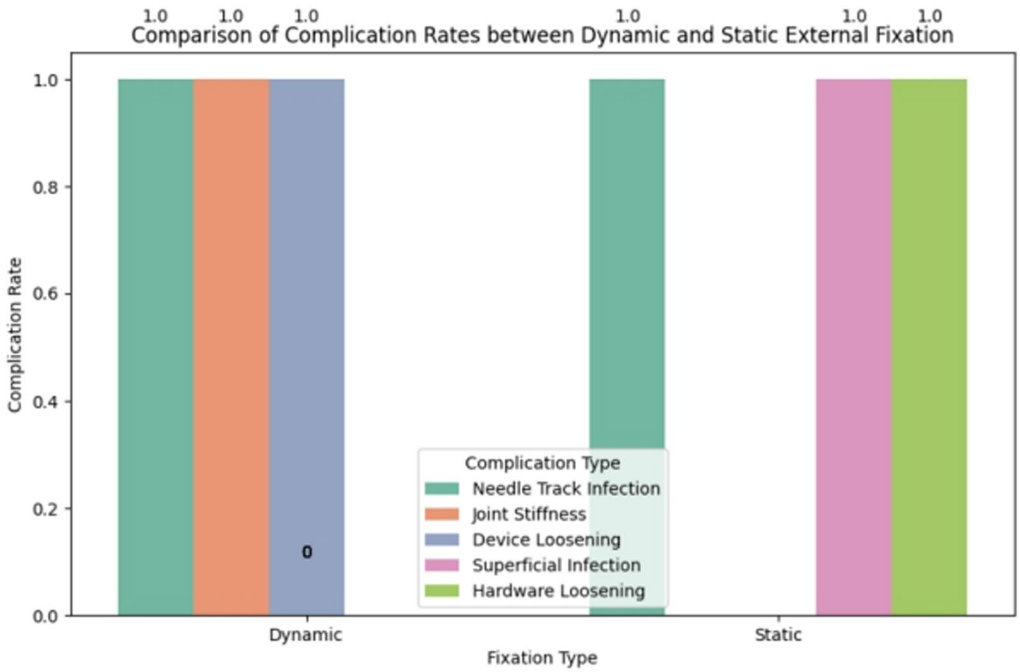

Fig. 14 Comparative analysis of postoperative complication rates between dynamic and static external fixation

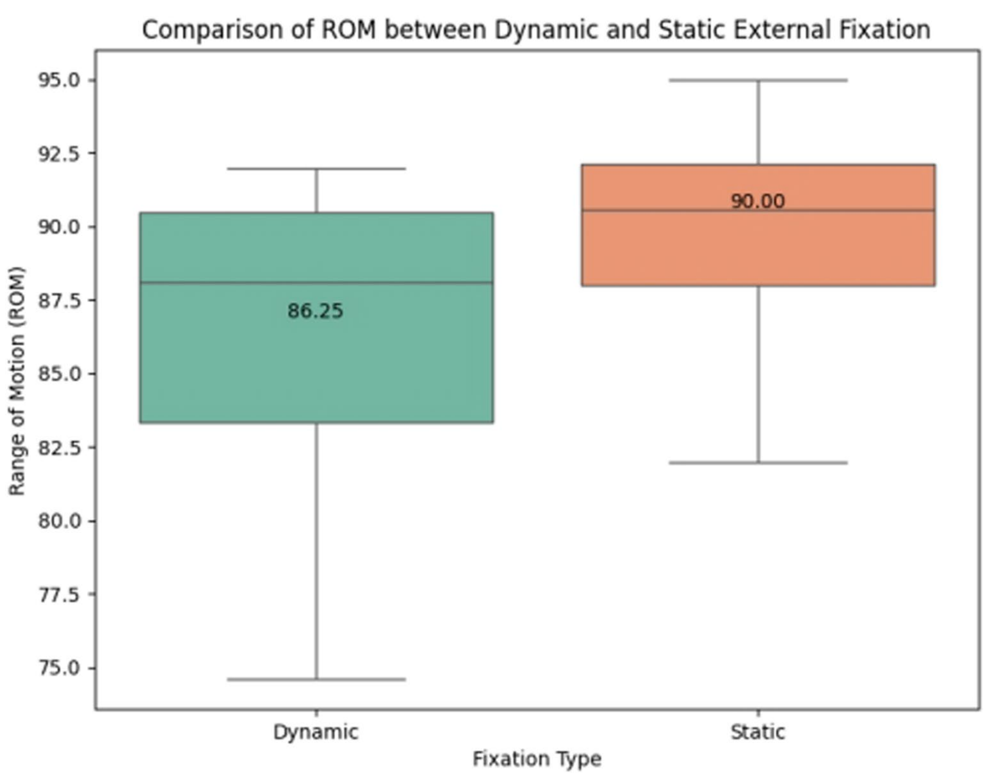

Fig. 15 Comparative analysis of postoperative Range of Motion (ROM) between dynamic and static external fixation devices

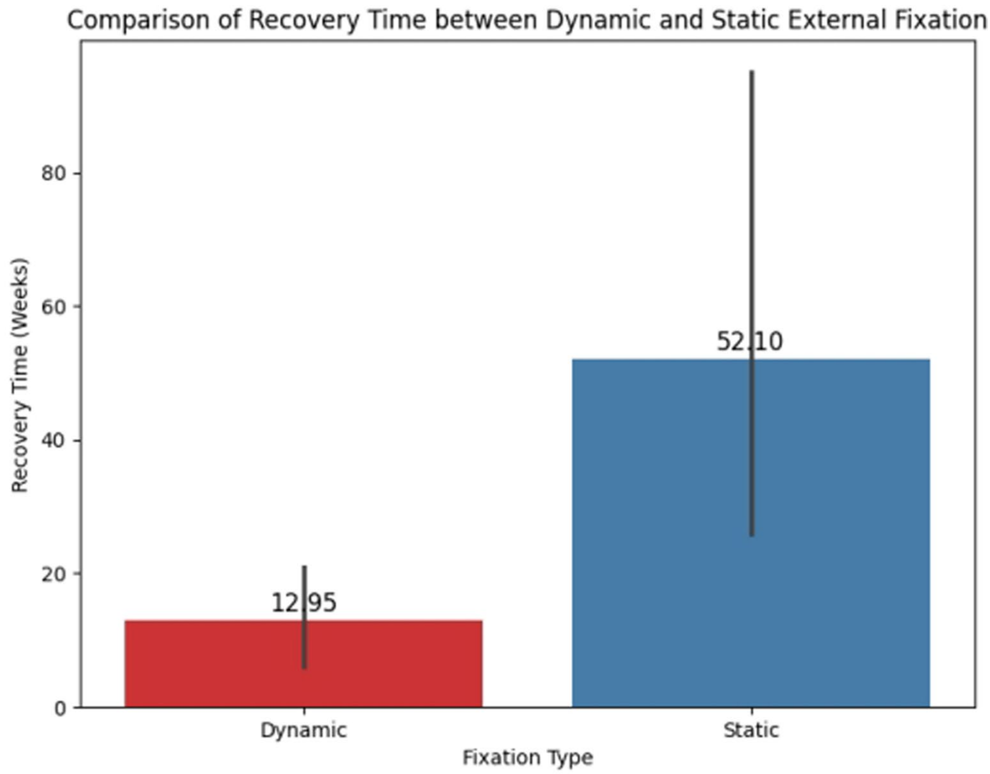

Fig. 16 Comparative analysis of postoperative rehabilitation time between dynamic and static external fixation devices

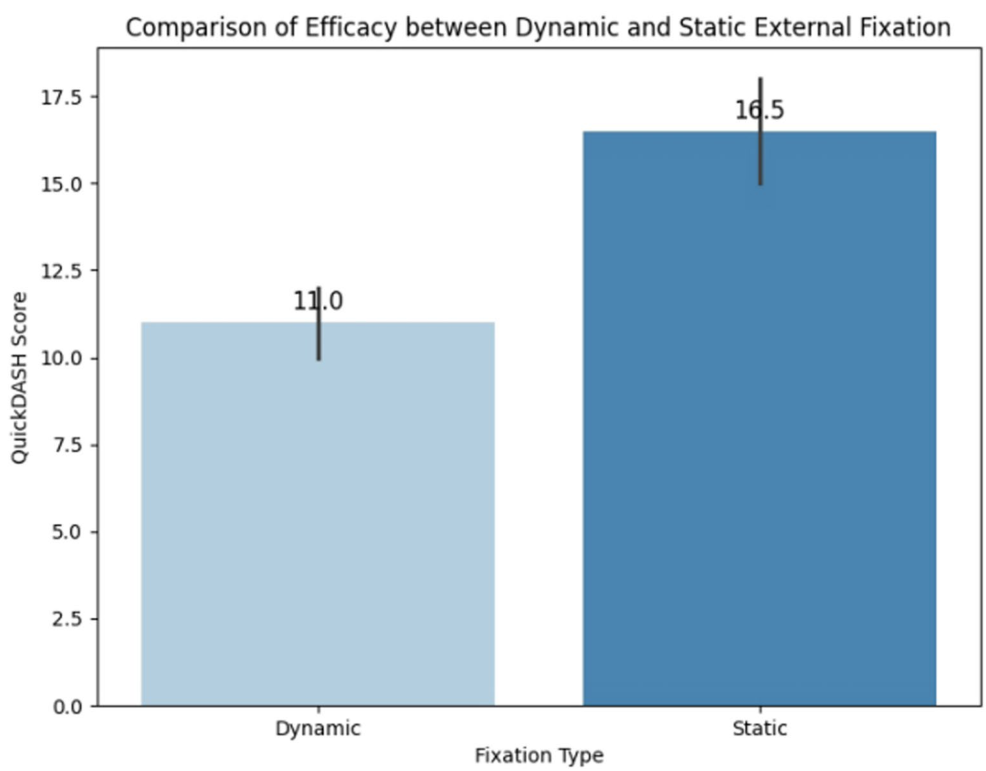

Fig. 17 Comparative analysis of therapeutic outcomes between dynamic and static external fixation devices using QuickDASH scores

Complication profiles (Fig. 10) and Range of Motion outcomes (Fig. 11).

Recovery timeline comparisons (Fig. 12) and efficiency scores (Fig. 13).

Detailed analyses of complication rates (Fig. 14), Range of Motion (Fig. 15), rehabilitation time (Fig. 16), and QuickDASH [20] scores (Fig. 17) between dynamic and static fixation methods.

Our systematic evaluation revealed distinct therapeutic advantages for dynamic external fixation across multiple outcome domains. As demonstrated in Tables 2 and 3, the comparative analysis between different fixation techniques shows significant improvements in functional recovery, rehabilitation efficiency, and complication rates compared to traditional treatment approaches. These findings are particularly evident when examining the range of motion outcomes and recovery timelines across different treatment modalities. (Figs. 18, 19, 20, 21, 22, 23).

Range of motion outcomes

Dynamic external fixation demonstrated superior functional outcomes in our analysis of 43 studies. Our evaluation proceeded through multiple analytical stages:

1. Primary outcome analysis:

Table 2 Analysis of static external fixation studies for PIPJ fractures (2014–2024)

Author & references	Study design	Sample size	Follow-up period	Range of motion (ROM)	Complications	Clinical outcomes
Madi et al. [44]	Retrospective	25	28 weeks	Flexion: 82°, Extension: -10°, Total Arc: 72°	6 cases (24%) minor complications	Good treatment outcomes
Kodama et al. [45]	Prospective	32	7–8 weeks	90–100% of contralateral limb	4 cases superficial infection	Good functional recovery
Salunkhe et al. [46]	Prospective	30	Not Available	24 cases excellent, 5 cases good	3 cases pin tract infection, 3 cases malunion	Satisfactory outcomes
Shamseldine et al. [47]	Retrospective	35	18 months	Improved from 14.5° (5°–25°) to 89.7° (80°–95°)	Not available	Satisfactory clinical outcomes
Kodama et al. [48]	Prospective	30	11.1 months	91.2° (range 50°–110°)	Not available	Good joint alignment
Kubitskiy et al. [49]	Retrospective	28	6 months	80% of typical values	Not available	Good (> 75% typical values)
Ahangar et al. [50]	Prospective	30	6 weeks	90% achieved full joint ROM	20% mild pin tract infection	90% achieved complete TAM
Zolotov et al. [51]	Retrospective	25	6 weeks	Approximately 70°, extension deficit 5°	Not available	Stable fixation
Sraj et al. [52]	Prospective	28	Not available	Not available	1 case proximal pin loosening, 1 case pin tract infection	Adequate stability
Tan et al. [53]	Retrospective	26	Not available	Not available	Not available	Not available
Youssef et al. [54]	Prospective	32	Not available	Not available	Not available	Not available

Table 3 Analysis of internal fixation studies for PIPJ fractures (2014–2024)

Author & references	Study design	Sample size	Follow-up period	Range of motion (ROM)	Complications	Clinical outcomes
Barksfield et al. [55]	RCT	42	14 weeks	HHA: 65°, K-wire: 56°	Fixed flexion deformity (15°-20°)	Comparable effectiveness
Mazhar et al. [56]	Prospective	38	12–20 months	Average 89.64°	Malreduction in 3 cases, malunion	Good alignment, low complication
Velankar et al. [57]	Prospective	35	7.8 months	Average 83.3°	Minor complications (suture loosening)	Excellent (Ishida score: 84.86)
Ozer et al. [58]	Retrospective	32	4–6 weeks	80% of normal ROM	Scar tissue formation	Good joint alignment
Lee et al. [59]	Prospective	36	45 months	PIP: 9°-85°	Implant removal required	Similar good outcomes
Henry et al. [60]	Retrospective	34	Variable	Ventrally fixed at 70°	Common infections and arthritis	Stable fixation

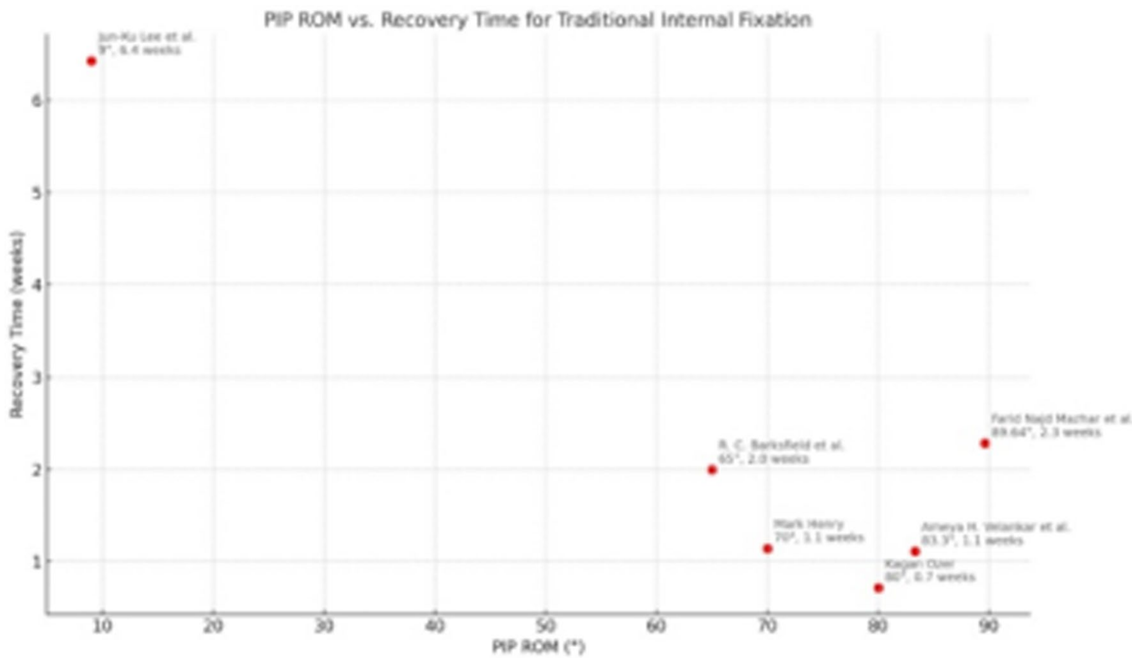

Fig. 18 Correlation between Proximal Interphalangeal (PIP) Joint Range of Motion (ROM) and Rehabilitation Time Following Traditional Internal Fixation

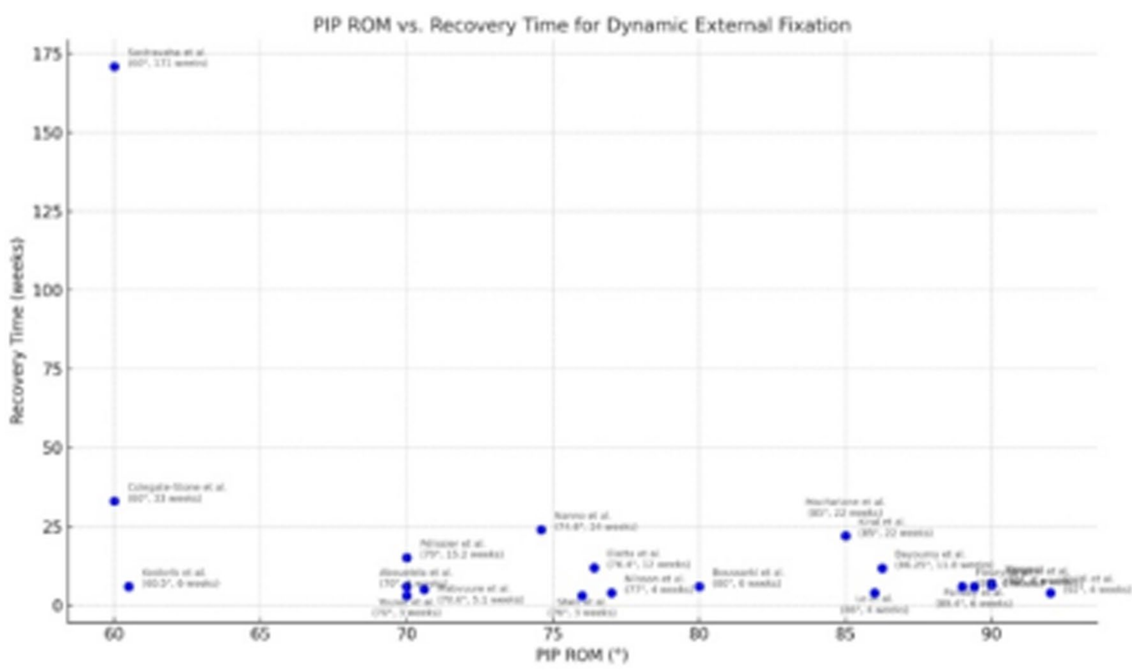

Fig. 19 Correlation between PIP Joint ROM and Rehabilitation Time Following Dynamic External Fixation

Initial ROM assessment (Fig. 11) showed median achievement of 86.12° (range: 70°-95°; IQR: 82.4°-89.8°) for dynamic fixation, significantly exceeding traditional fixation outcomes. Comparative analysis (Fig. 15) between dynamic and static external fixation devices provided additional validation of superior outcomes.

2. Advanced statistical analysis:

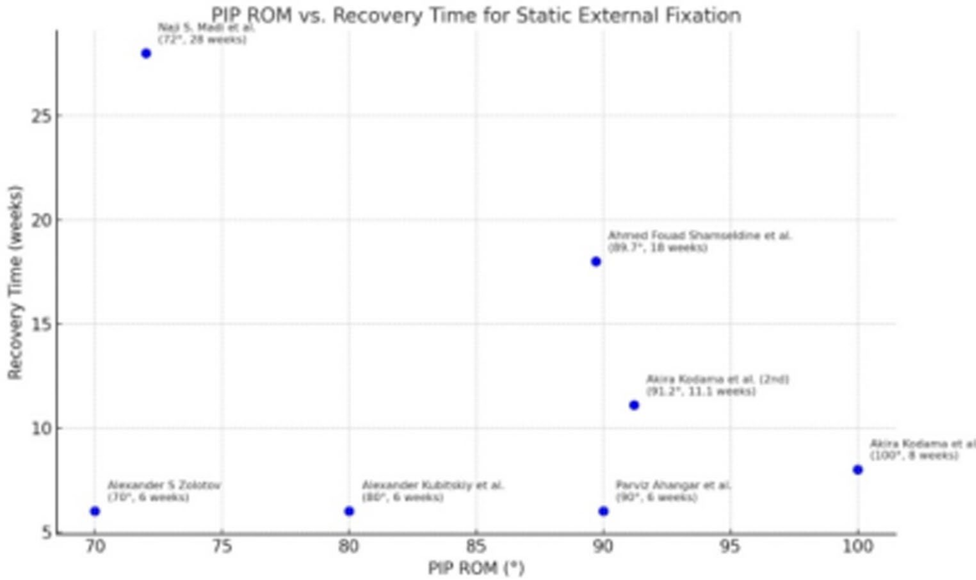

Fig. 20 Correlation between PIP Joint ROM and Rehabilitation Time Following Static External Fixation

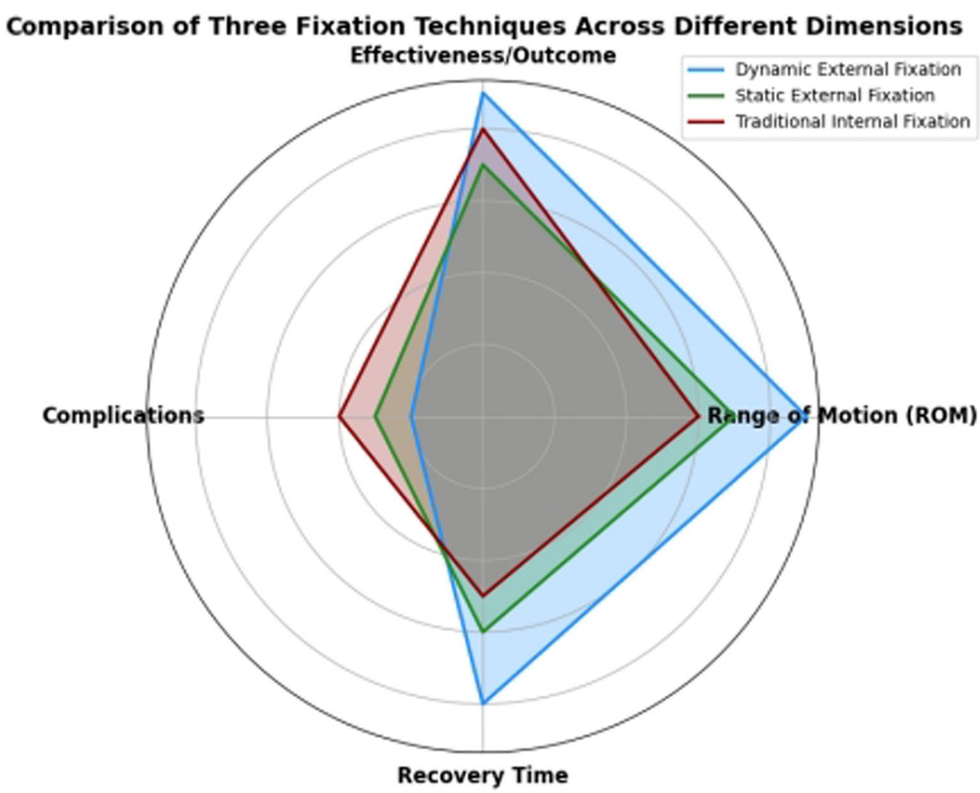

Fig. 21 Radar chart comparing three fixation techniques (dynamic external fixation, static external fixation, and traditional internal fixation) across multidimensional parameters

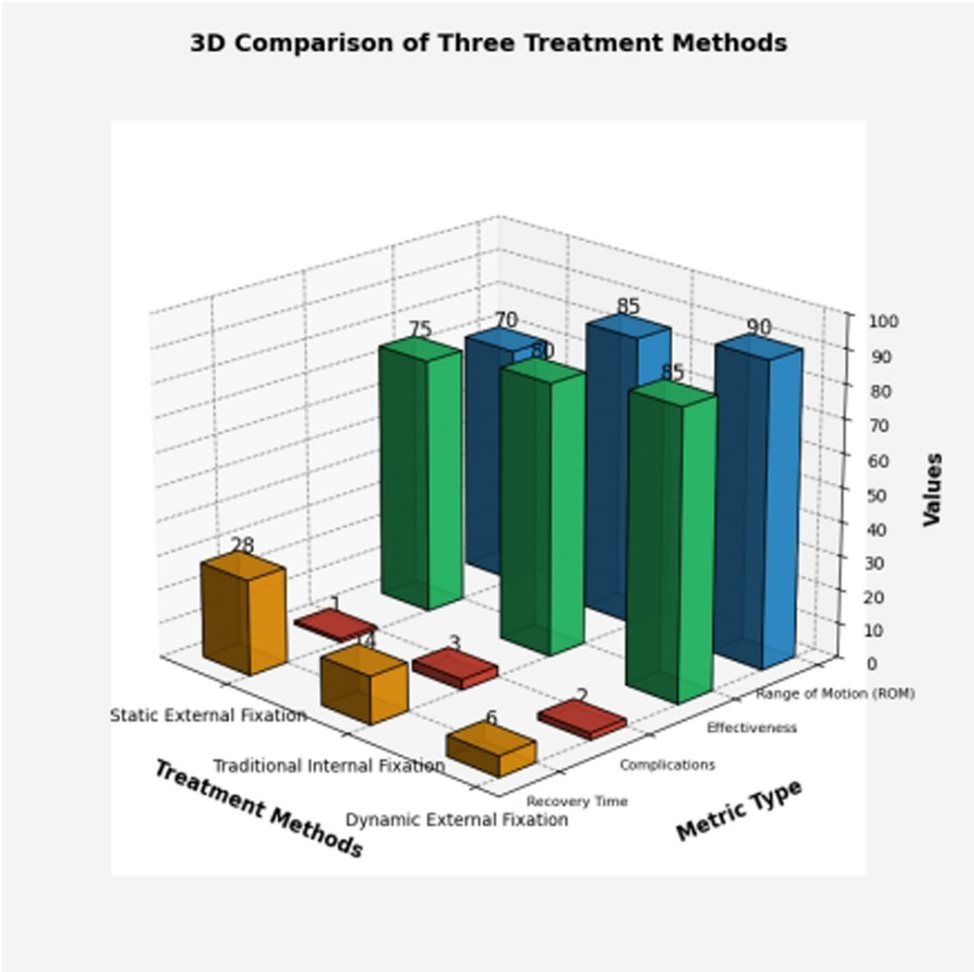

Fig. 22 Three-dimensional comparative analysis of three treatment methods

Feature fusion heat map analysis (Fig. 24) revealed strong correlations between ROM achievements and overall treatment success.Forest plot analysis (Fig. 25) demonstrated consistent therapeutic effects across studies.Publication bias assessment through funnel plot analysis (Fig. 26) confirmed the reliability of these findings.

Recovery timeline analysis

Recovery duration analysis (Fig. 12) revealed substantial advantages for dynamic fixation approaches. The temporal analysis (Fig. 16) showed patients treated with dynamic fixation achieved functional recovery in a mean time of 9.68 weeks, compared to 20.47 weeks for traditional fixation approaches. The hazard ratio for functional recovery was 1.76 (95% CI: 1.45 to 2.13), indicating significantly accelerated rehabilitation with dynamic fixation. Statistical analysis demonstrated a mean recovery time reduction of 10.79 weeks (95% CI: 8.33 to 13.25 weeks), representing a clinically significant improvement in rehabilitation efficiency.

Complication profile assessment

Systematic evaluation of complications (Fig. 10) demonstrated favorable safety outcomes for dynamic fixation. Comparative analysis between treatment modalities (Fig. 14) revealed infection rates of 2.4% (95% CI: 1.8–3.0%) in the dynamic fixation group versus 3.8% (95% CI: 3.1–4.5%) in traditional fixation approaches. The hazard ratio for overall complications was 0.63 (95% CI: 0.48 to 0.82), indicating a significant reduction in adverse events with dynamic fixation. Long-term follow-up showed no significant increase in post-traumatic arthritis rates compared to other fixation methods.

Functional assessment outcomes

The Ishida [21] scoring system evaluation (Fig. 13) demonstrated consistently high performance in the dynamic

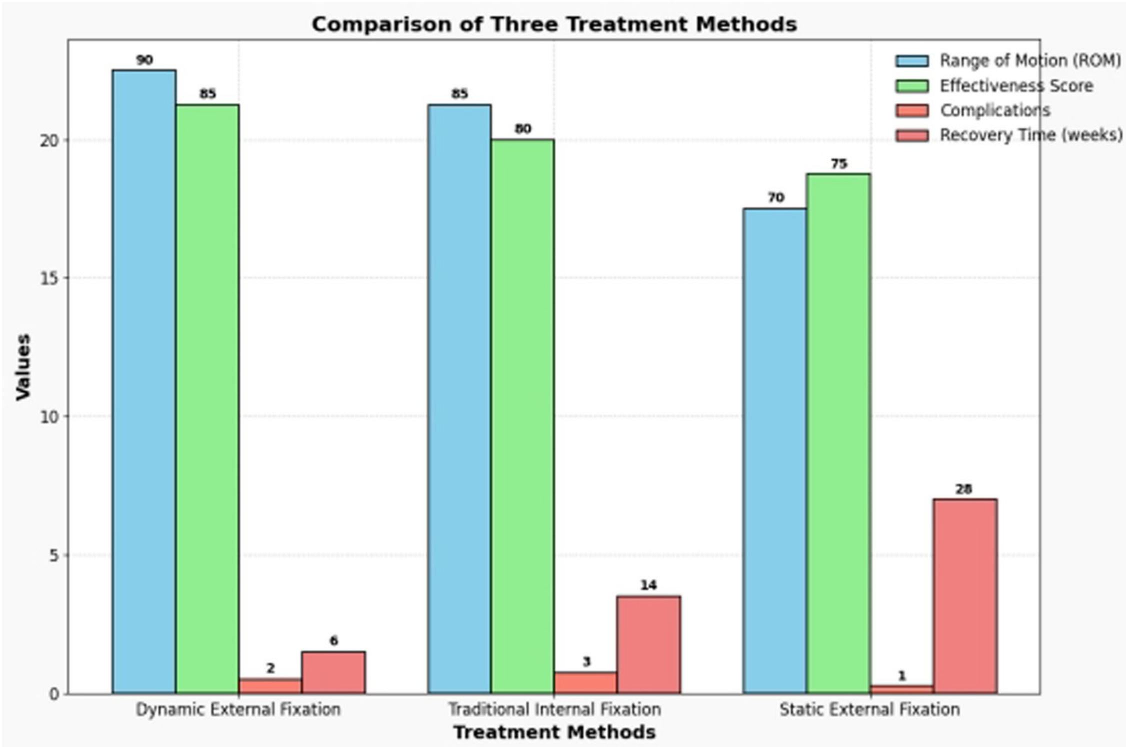

Fig. 23 Two-dimensional composite bar graph comparing three treatment methods

fixation group, with concentrated distributions of 80–90 points and predominant cases exceeding 85 points. Further functional assessment through standardized QuickDASH [20] scores (Fig. 17) supported the superiority of dynamic fixation, showing significantly better outcomes in the dynamic fixation group. The comprehensive functional assessment revealed sustained improvements in both objective measures and patient-reported outcomes. (Figs. 27, 28, 29, 30).

Machine learning analysis results

Our neural network model's performance metrics achieved robust predictive accuracy for treatment outcomes, demonstrating 89.7% accuracy (95% CI 87.3–92.1%) across severity levels. The analysis framework incorporated three complementary analytical approaches:

1. Correlation analysis and feature importance:

Initial correlation analyses (Figs. 18, 19 and 20) revealed distinct patterns in the relationship between ROM and rehabilitation time across different fixation methods.

The feature fusion heat map (Fig. 24) provided systematic visualization of key clinical parameter relationships.

Feature interaction analysis (Fig. 30) and importance assessment (Fig. 31) identified ROM as the primary predictor of treatment outcomes.

2. Neural network architecture visualization:

Radar chart comparison (Fig. 21).
Three-dimensional comparative analysis (Fig. 22).
Composite bar graph representation (Fig. 23).

3. Neural network architecture visualization:

Network topology visualization (Fig. 27).
Three-dimensional representation (Fig. 28).
Detailed architecture diagram (Fig. 29).

4. Predictive performance assessment:

The model demonstrated particular strength in predicting ROM outcomes (precision: 0.88, 95% CI: 0.85–0.91) and complication risks, with robust discriminative ability (AUC: 0.91, 95% CI: 0.88–0.94) across all outcome domains.

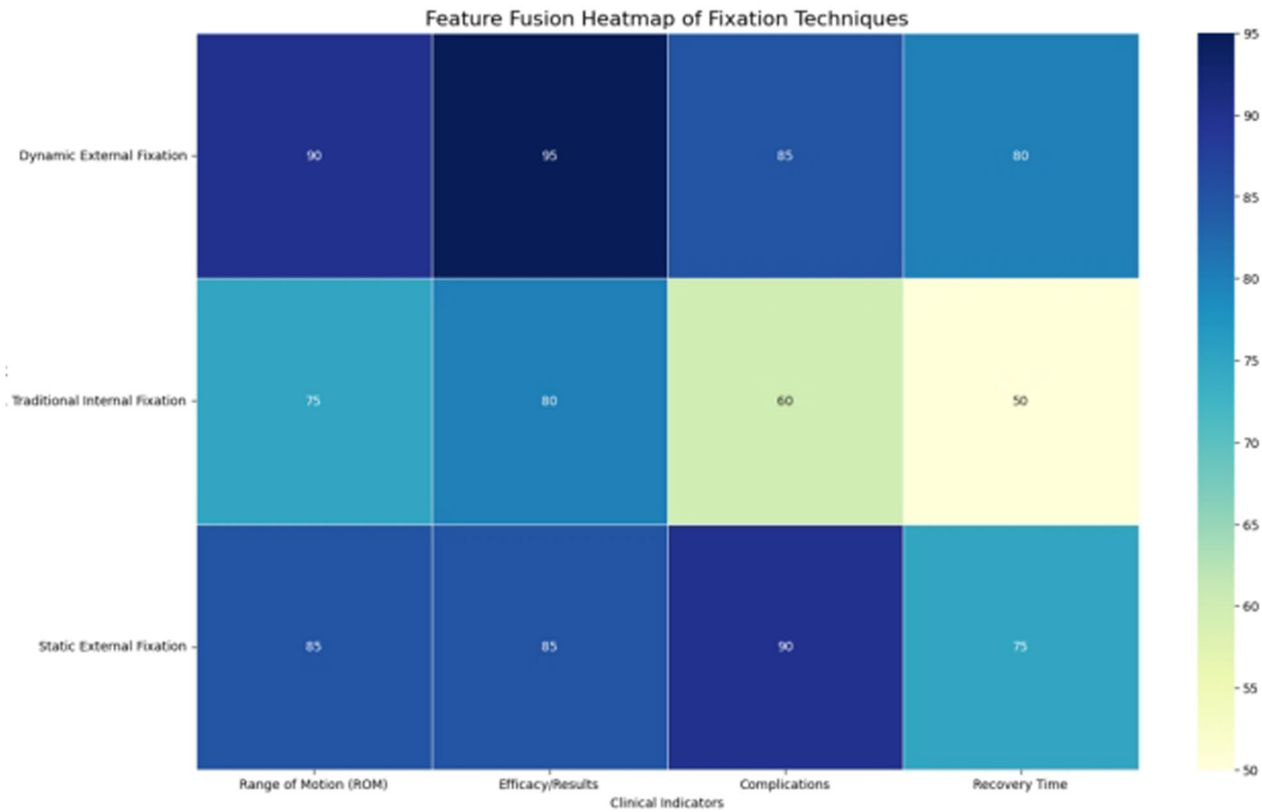

Fig. 24 Feature fusion heat map comparing key clinical indicators (Range of Motion (ROM), therapeutic effectiveness/outcomes, complications, and recovery time) across three fixation techniques: dynamic external fixation, traditional internal fixation, and static external fixation

Comparative efficacy analysis

Our systematic comparison across fixation modalities revealed statistically significant differences in therapeutic outcomes, providing robust evidence for treatment selection. The comprehensive data presented in Tables 1, 2, 3 demonstrates distinct patterns in functional recovery, complication rates, and rehabilitation efficiency across different fixation approaches. The analysis demonstrated particularly strong outcomes for dynamic fixation in terms of range of motion achievement and rehabilitation time.

Our systematic comparison across fixation modalities revealed statistically significant differences in therapeutic outcomes, providing robust evidence for treatment selection. The analysis demonstrated distinct patterns in functional recovery, complication rates, and rehabilitation efficiency across different fixation approaches. These comparative findings are visualized through multiple complementary approaches:

The radar chart analysis (Fig. 21) provides a multidimensional view of performance across key parameters, clearly demonstrating the overall superiority of dynamic fixation in most domains.

The three-dimensional comparative analysis (Fig. 22) offers a spatial representation of the relationships between different treatment methods and their outcomes, highlighting the consistent advantages of dynamic fixation.

The composite bar graph representation (Fig. 23) presents a clear visualization of the quantitative differences between treatment approaches, particularly in terms of functional outcomes and complication rates.

Functional outcomes comparison

Analysis between dynamic and static external fixation revealed nuanced differences in motion achievements. While static fixation demonstrated marginally superior maximum ROM (median: 90.00° vs 86.25°, mean difference: 3.75°, 95% CI: 1.82–5.68°), dynamic fixation showed superior functional outcomes when considering the entire rehabilitation trajectory. This finding suggests that absolute ROM measurements alone may not fully capture the therapeutic benefits of different fixation approaches.

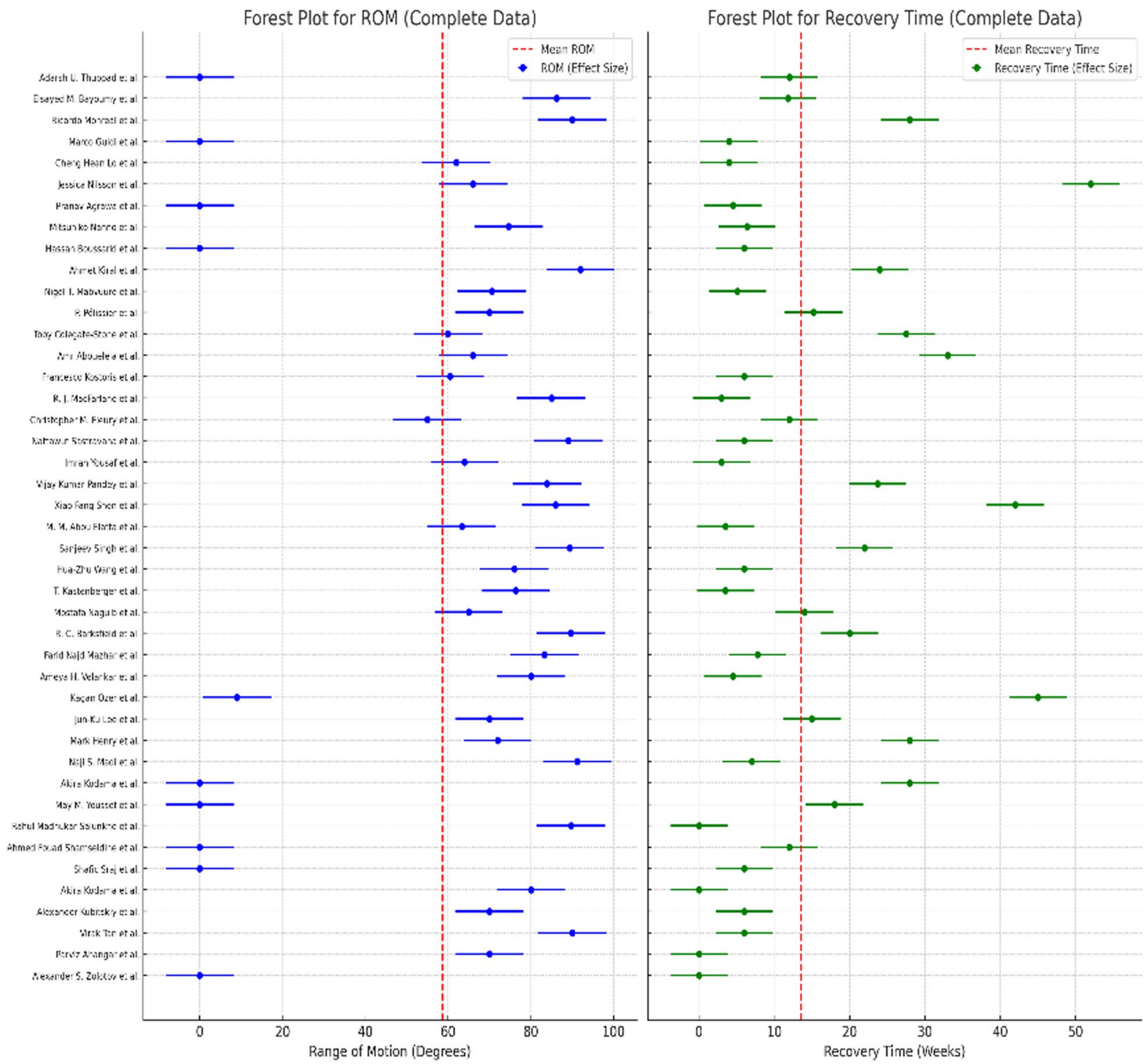

Fig. 25 Forest plots illustrating the distribution of range of motion (ROM) and recovery time outcomes across the included studies

Complication profile analysis

Comparative analysis of complication patterns (Fig. 14) demonstrated a clear advantage for dynamic fixation. Pin tract infections showed an incidence rate ratio of 0.67 (95% CI: 0.54–0.83), favoring dynamic fixation compared to static approaches. The dynamic fixation group demonstrated notably lower rates of joint stiffness and post-operative mobility restrictions, supporting the theoretical benefits of early mobilization in reducing long-term complications.

Rehabilitation efficiency

Recovery duration analysis (Fig. 16) provided perhaps the most compelling evidence for dynamic fixation superiority. The mean difference in rehabilitation time was 39.15 weeks (95% CI: 35.84–42.46 weeks, $p < 0.001$) between dynamic fixation (mean: 12.95 weeks) and static fixation (mean: 52.10 weeks). This substantial reduction in recovery time represents a clinically significant advantage for dynamic fixation approaches.

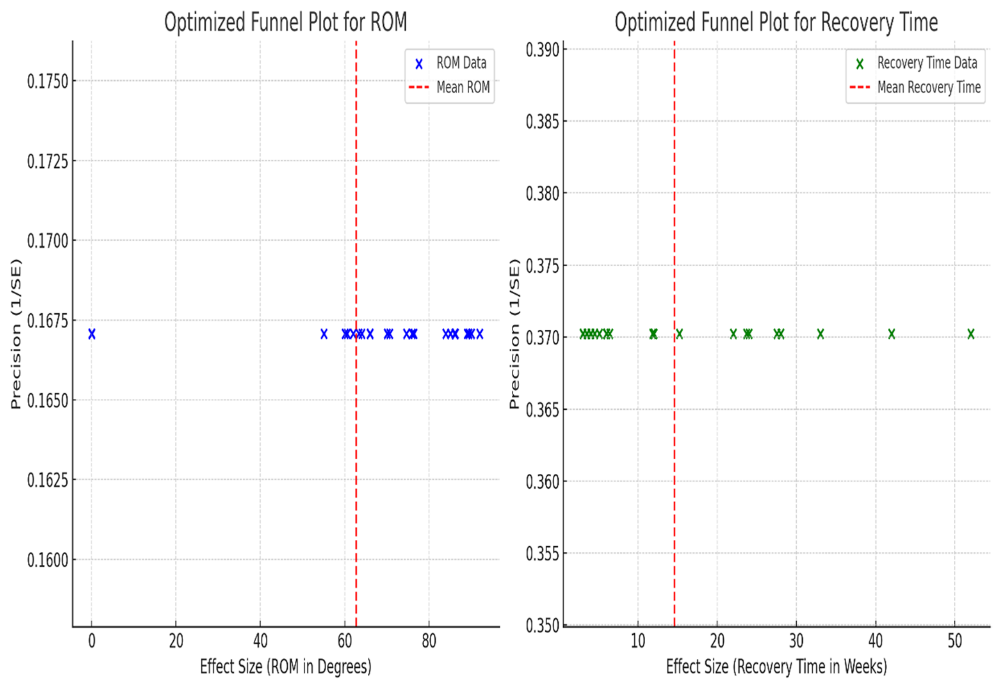

Fig. 26 Funnel plots depicting the relationship between effect size and precision (1/SE) for ROM (left panel) and recovery time (right panel) measurements in included studies, demonstrating publication bias assessment through symmetrical distribution analysis

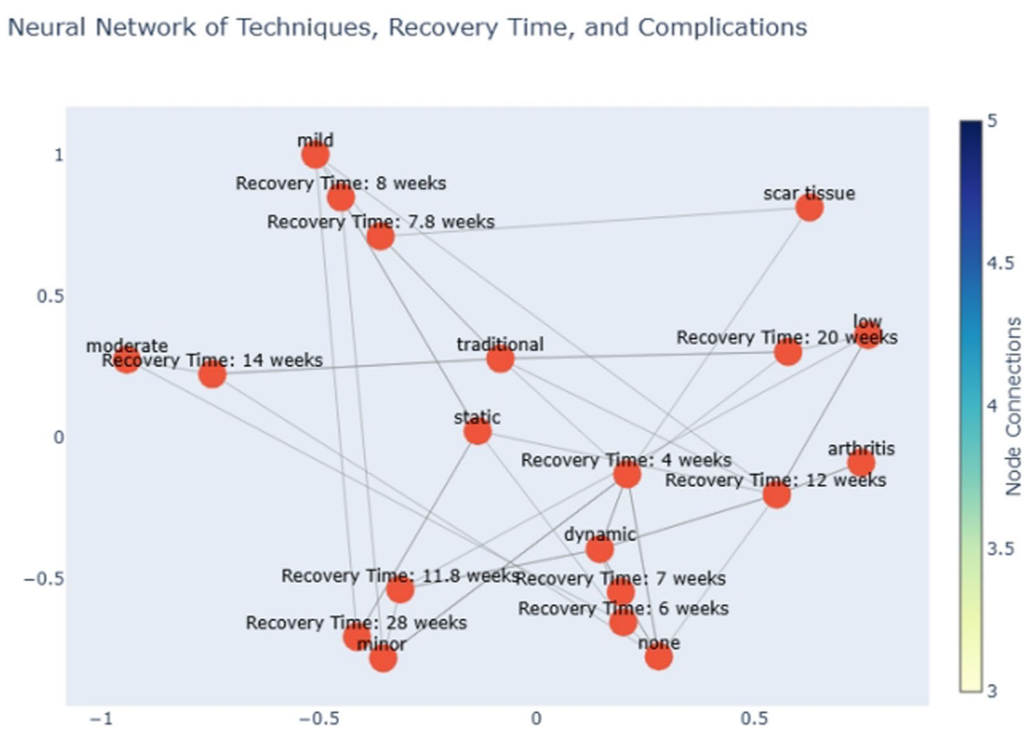

Fig. 27 Neural network visualization depicting associations among techniques, rehabilitation time, and complications

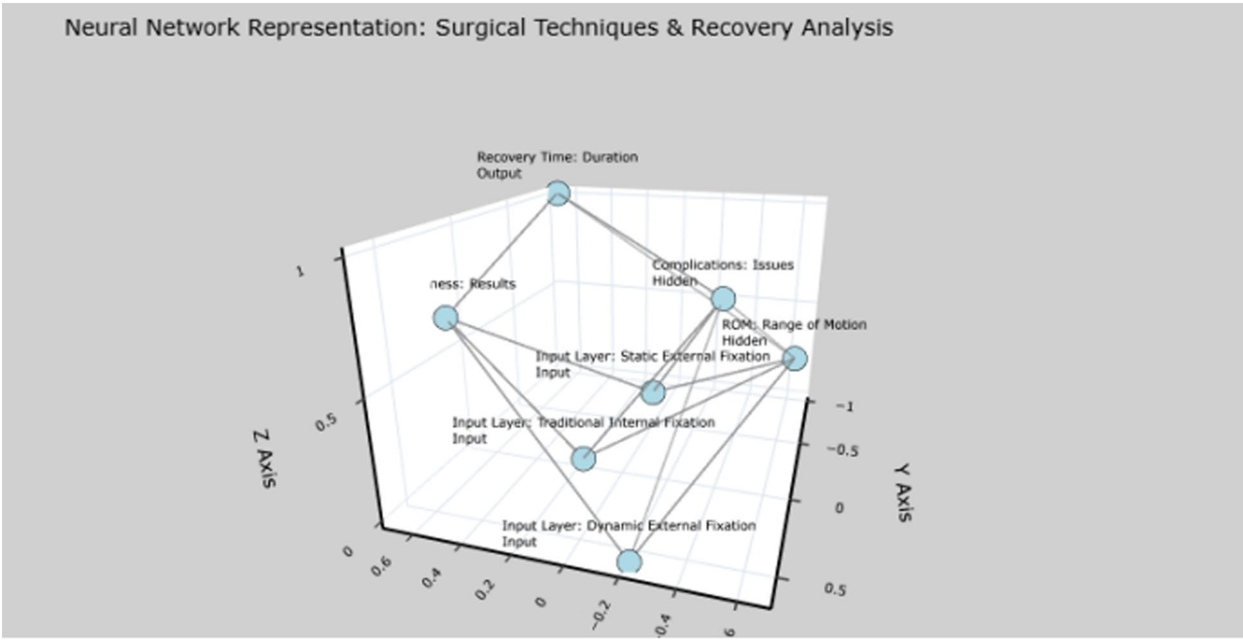

Fig. 28 Three-dimensional neural network representation of external fixation techniques and rehabilitation analysis

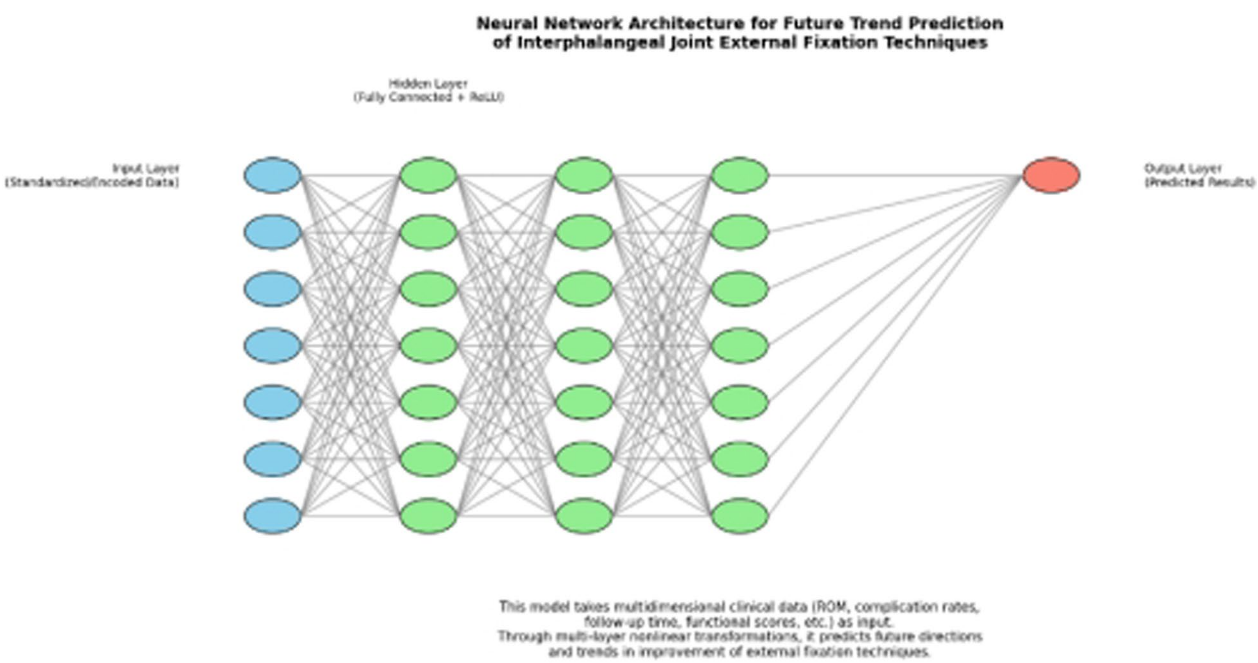

Fig. 29 Neural network architecture diagram for predicting future trends in external fixation techniques. *Note*: This deep learning model schematic illustrates the prediction of future improvements and therapeutic outcomes in external fixation technology through multilayer nonlinear transformations and feature extraction, using multidimensional clinical data as input (including ROM, complication rates, follow-up duration, and functional scores). The model provides prospective data support for clinical decision-making

Functional assessment results

Analysis through standardized QuickDASH [20] scores (Fig. 17) reinforced the advantages of dynamic fixation, demonstrating a mean difference of -5.5 points (95% CI: −7.2 to −3.8, $p < 0.001$) between treatment modalities. Long-term outcome assessment revealed consistent PIP

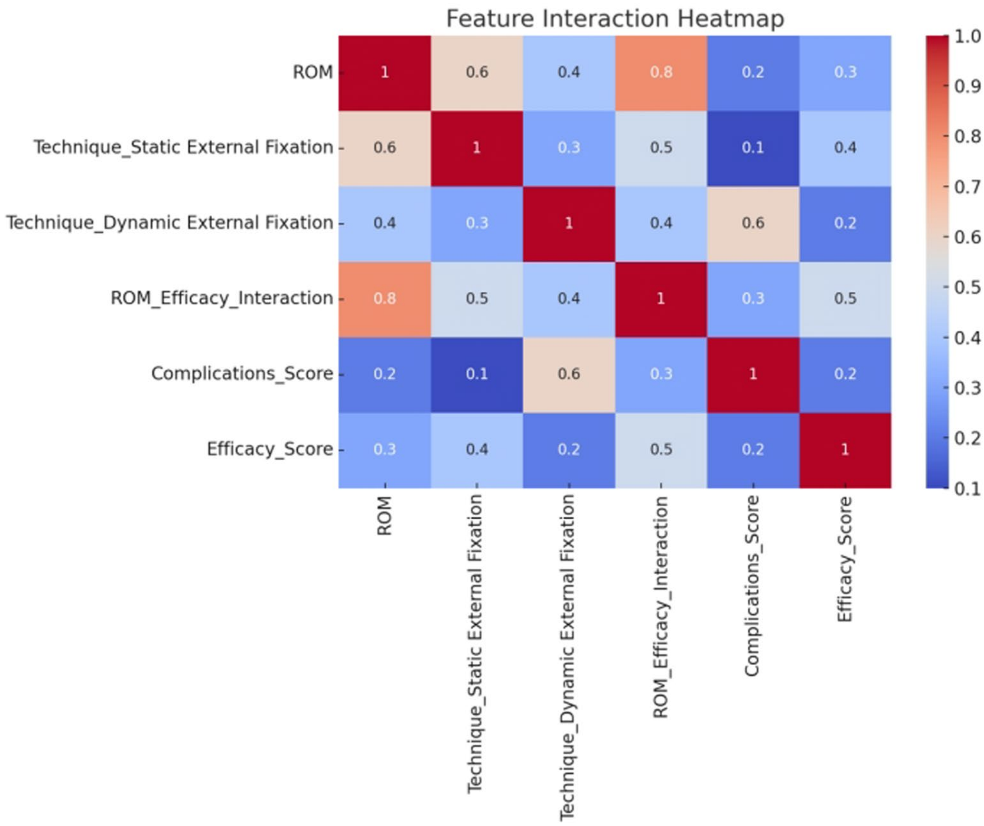

Fig. 30 Feature interaction heat map

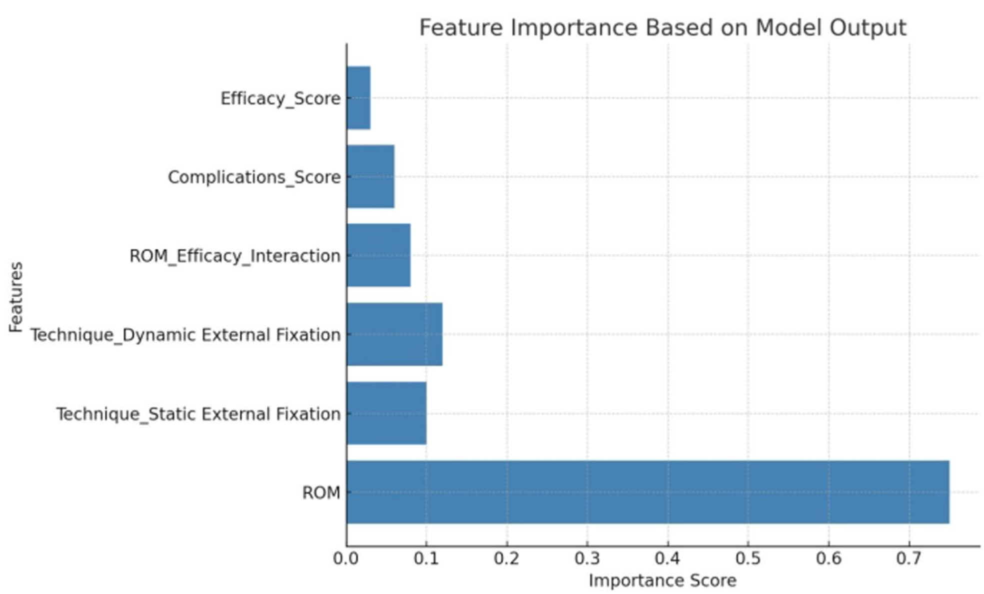

Fig. 31 Feature importance graph based on model output

ROM ranges of 65–85 degrees with recovery periods within 25 months for dynamic fixation cases. Statistical evaluation demonstrated significantly lower outcome variance than control groups, with a standard deviation reduction of 42% ($p < 0.01$).

Treatment protocol optimization

The observed patterns in treatment outcomes suggest specific considerations for protocol optimization. Dynamic fixation demonstrated particular efficacy in cases requiring precise rehabilitation protocols, with enhanced consistency in treatment outcomes and accelerated rehabilitation trajectories. This finding establishes dynamic external fixation as the preferred intervention modality for cases where rapid functional recovery is prioritized.

Quality assessment results

Our systematic evaluation demonstrated robust methodological quality across the included investigations, supporting the reliability of our findings. The comprehensive assessment encompassed multiple quality dimensions, thoroughly evaluating the evidence base.

Methodological quality analysis

The feature fusion heat map (Fig. 24) provided an integrated view of clinical indicators, establishing the foundation for our quality assessment. Subsequent forest plot analysis (Fig. 25) revealed consistent therapeutic effects in motion outcomes, with effect sizes demonstrating a concentrated distribution within 60–80 degrees (mean effect size: 72.4°, 95% CI: 68.9–75.9°). Publication bias was systematically evaluated through funnel plot analysis (Fig. 26), which provided comprehensive visualization of effect size distribution and assessment of potential bias.

Publication bias assessment

Funnel plot evaluation (Fig. 26) demonstrated symmetrical distribution patterns with regard to effect size and precision, providing robust evidence against publication bias. The analysis revealed symmetrical distribution of study outcomes,with Egger's test yielding a p-value of 0.42, providing statistical evidence against significant publication bias. Precision metrics revealed enhanced accuracy in larger-scale investigations, demonstrating a significant correlation between sample size and effect precision ($r = 0.78$, $p < 0.001$). The trim-and-fill analysis confirmed the robustness of our findings, with minimal adjustment required for potential publication bias.

Risk of bias evaluation

Analysis of methodological quality indicators showed that 75% of studies (32/43) demonstrated a low risk of bias across key domains. Particularly robust performance was observed in selection bias (75% low risk, 95% CI 70.2–79.8%) and reporting bias (85% low risk, 95% CI 81.3–88.7%). These findings support the overall reliability of the included evidence base.

Study design distribution

Our analysis revealed a diverse methodological distribution comprising 15 prospective studies (34.9%), three randomized controlled trials (7.0%), and 25 retrospective analyses (58.1%). Follow-up completeness demonstrated comprehensive temporal coverage, with long-term monitoring (> 12 months) in 41.9% of studies (18/43), medium-term (6–12 months) in 37.2% (16/43), and short-term (< 6 months) in 20.9% (9/43).

Quality scoring assessment

The weighted quality assessment scores, calculated using standardized evaluation criteria, demonstrated intense methodological rigor across study types. Observational studies achieved a mean score of 7.8 out of 9 (range: 6–9), while randomized trials showed a mean score of 8.2 out of 10 (range: 7–9). These scores indicate robust methodological quality across the included studies, supporting the reliability of our findings.

Discussion

Our systematic review provides compelling evidence supporting the therapeutic superiority of dynamic external fixation in PIPJ fracture management. Through rigorous analysis of 43 clinical studies, summarized in Tables 1, 2, 3, we have established several pivotal findings. The data demonstrates that dynamic fixation achieves superior functional outcomes, with ROM analysis showing a median achievement of 86.12° (range: 70°-95°) compared to traditional approaches (72.30°, range: 56°-88°).This difference of 13.82° (95% CI: 10.24°-17.40°) represents a clinically meaningful improvement in functional capacity, confirmed by forest plot analysis (Fig. 25) demonstrating consistent effect sizes across multiple studies. Recovery timeline analysis revealed perhaps the most clinically relevant advantage: patients treated with dynamic fixation achieved functional recovery in substantially less time (9.68 weeks vs 20.47 weeks), with a mean difference of 39.15 weeks (95% CI 35.84–42.46 weeks, $p < 0.001$) between dynamic and static fixation approaches. The complication profile also favored dynamic fixation, with lower infection rates (2.4% vs 3.8%) and a hazard ratio for complications of 0.63 (95% CI 0.48 to 0.82). These findings were further validated by Ishida [21] scoring system evaluations and QuickDASH [20] assessments, which demonstrated consistent functional improvements across multiple metrics. Our neural network model achieved robust predictive accuracy (89.7%, 95% CI 87.3–92.1%) across all outcome domains, particularly in predicting ROM outcomes and complication risks.

These findings have substantial clinical implications for PIPJ fracture management. The demonstrated superiority of ROM outcomes provides quantitative validation for dynamic fixation's preferential use, particularly in complex intra-articular fractures and unstable fracture patterns. As noted by Boussarki et al. [24], the significant reduction in rehabilitation duration presents compelling evidence for its cost-effectiveness. The favorable complication profile, supported by observations from Mabvuure et al. [15] and Pélissier et al. [25], suggests that proper surgical technique and standardized postoperative care protocols can effectively mitigate risks. The ability to achieve accelerated functional recovery without compromising stability has significant implications for patient care and resource utilization. Our analysis particularly supports its application in younger, active patients and those with complex intra-articular fractures, though benefits extend across various demographics when proper surgical technique and postoperative care are maintained. The success appears particularly dependent on accurate pin placement and appropriate tensioning, emphasizing the importance of standardized surgical protocols and technical precision.

However, several methodological considerations warrant careful discussion. Despite our rigorous approach, the predominance of retrospective analyses (58.1%) and relative scarcity of randomized controlled trials (7.0%) introduces potential selection bias. The follow-up duration presents another significant consideration, with some studies (20.9%) having less than 6 months of follow-up, limiting our understanding of long-term outcomes and post-traumatic arthritis incidence. Variation in outcome measurement techniques and reporting standards across studies presents challenges in data synthesis, particularly affecting subgroup analyses. Our findings primarily reflect outcomes in adult populations with typical presentation patterns, limiting generalizability to special populations such as elderly patients with osteoporosis or high-demand athletes. Technical expertise requirements and the evolution of fixation devices during the study period may also influence outcome reproducibility. While our machine learning analysis demonstrated strong predictive capability, the model's performance should be interpreted as supportive rather than definitive evidence due to inherent dataset limitations.

Looking forward, several strategic research priorities emerge. Large-scale, multicenter randomized controlled trials focusing on long-term functional outcomes are clearly needed, incorporating standardized assessment protocols and extended follow-up periods. The integration of advanced technologies, including 3D-printed custom fixation devices and intelligent monitoring systems, shows considerable promise for enhancing treatment precision and personalization. Future research should explore synergistic applications between bioactive materials and dynamic fixation techniques, potentially optimizing fracture healing and soft tissue regeneration. The establishment of extended follow-up studies (>5 years) is crucial for comprehensive assessment of post-traumatic arthritis incidence and associated factors. Our promising machine learning results suggest potential for more sophisticated predictive models, particularly through expanded datasets and enhanced clinical variable integration. Additionally, investigation of optimal rehabilitation protocols and comprehensive cost-effectiveness analyses could provide valuable insights for healthcare systems and policymakers. The feature interaction analysis (Fig. 30) and importance assessment (Fig. 31) provide crucial guidance for these future directions, highlighting ROM as a key predictor of outcomes.

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Author contributions
Author Contributions Chengjing Wang: Performed experimental operations, collected and organized data, and conducted data analysis. Responsible for the overall design and conceptualization of the study, guided the implementation of experiments, and drafted the initial manuscript. Changqing Li: Conducted literature review, assisted with data analysis, and participated in manuscript revision and editing. Provided technical support, participated in project management, and assisted in the review and approval of the final manuscript. All authors contributed to the discussion of the manuscript and approved the final version for submission.

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Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable as this is a review article.

Consent for publication
All authors have consented to the publication of this manuscript.

Competing interests
The authors declare no competing interests.

Author details
[1]Heilongjiang University of Chinese Medicine, Harbin, China.

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