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RESEARCH

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Biomechanical study of a modified application of Ilizarov external mini-fixator for metacarpal neck fractures: a comparative analysis

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Abstract

Background Metacarpal neck fractures are common and there are numerous surgical methods available, but each has certain disadvantages and limitations. We modified the conventional Ilizarov external mini-fixator and this study is designed to compare the biomechanical stability of a modified Ilizarov external mini-fixator with conventional fixation methods for metacarpal neck fractures and to provide a basis for its clinical application.

Methods Forty fresh porcine metacarpal specimens were used to create metacarpal neck fracture models. The specimens were randomly assigned to four fixation groups ($n = 10$) as follows: (1) modified Ilizarov external mini-fixator (IEF), (2) retrograde crossed Kirschner wires (KW), (3) antegrade intramedullary Kirschner wires (IK), and (4) locking plate fixation (LP). In the IEF group, the modified design involved crossing two Kirschner wires (K-wires) through the fracture line, with their tails bent twice and connected to the external fixator frame. Biomechanical testing was performed using a modified three-point bending test. Maximum fracture force and bending stiffness were calculated from the force-displacement curves. Kruskal–Wallis test was used to compare statistical differences in maximum fracture force and stiffness among the groups, followed by post hoc pairwise comparisons adjusted with Bonferroni corrections.

Results The median maximum fracture force values (± interquartile range, IQR) for each group were as follows: IEF 160.3 ± 55.6 N, LP 173.5 ± 42.6 N, KW 91.1 ± 23.1 N, and IK 79.8 ± 37.8 N. The corresponding stiffness values were as follows: IEF 29.5 ± 10.4 N/mm, LP 32.9 ± 10.4 N/mm, KW 17.2 ± 11.3 N/mm, and IK 18.2 ± 13.7 N/mm. The IEF group demonstrated significantly higher maximum fracture force and stiffness than the KW and IK groups; however, no statistically significant differences were observed in the IEF group compared with the LP group.

Conclusion The modified Ilizarov external mini-fixator provided significantly greater biomechanical stability for metacarpal neck fractures than retrograde crossed K-wires and antegrade intramedullary K-wires, achieving comparable performance to the locking plate system. This modified design combines the simplicity and minimally invasive advantages of K-wire fixation with enhanced stability, potentially facilitating early joint mobilization and minimizing the risk of complication.

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Keywords Ilizarov external mini-fixator, Metacarpal neck fractures, Biomechanical study, Modified application

Background

The metacarpal neck is the most common site of fracture in the metacarpals, accounting for approximately two-thirds of all metacarpal fractures and 20% of all hand fractures [1–2]. These fractures primarily occur in the fourth and fifth metacarpals [3], usually due to direct trauma, such as forceful fist clenching. The combination of axial energy transmission through the metacarpal and traction forces exerted by the interosseous muscles results in angular deformities characterized by dorsal prominence. Effective reduction and fixation are crucial for preserving the functional integrity and aesthetic appearance of the affected hand. Most metacarpal neck fractures can be successfully managed with non-surgical interventions, such as closed reduction followed by fixation with splints, casts, or buddy straps [4–8]. However, surgery is indicated in cases of significant shortening, rotational malignment, or angular deformity [9]. Despite the need for surgical fixation in such cases, the precise indications for surgical intervention remain a subject of ongoing debate [10–12].

Currently, several surgical fixation methods are available for the treatment of metacarpal neck fractures, including retrograde crossed Kirschner wires (K-wires), antegrade intramedullary Kirschner K-wires, intramedullary screws, locking plate-screw systems, and external fixators. Each method offers distinct advantages and disadvantages; however, the optimal fixation technique in basic and clinical research has not been fully established [12–15].

Retrograde crossed K-wire fixation, a more traditional approach, is simple and minimally invasive but provides limited stability, often necessitating additional external support with a cast or splint. Common complications associated with this method include loss of reduction and pin-track infections [16–19]. Antegrade intramedullary K-wire and intramedullary screw fixation offer improved axial stability, but poor rotational control [20]. Furthermore, the bending resistance of antegrade K-wires is not superior to that of retrograde crossed K-wires, often requiring additional external support for adequate stability and presenting similar potential complications. Intramedullary screws offer greater stability than K-wires [21–22], but their insertion may damage the articular cartilage, increasing the long-term risk of arthritis and joint stiffness [23–24].

Locking plate fixation provides excellent mechanical stability, facilitating early rehabilitation. However, its application necessitates open reduction and plate placement, resulting in more extensive surgical trauma and potentially disrupting the blood supply to the fracture site. This fixation method carries a higher risk of joint capsule and extensor tendon damage, leading to complications such as joint stiffness and tendon adhesions [25–26]. Furthermore, a second surgery for plate removal is required, increasing patients' burden.

External fixation, although commonly used for metacarpal shaft and base fractures, is less frequently applied to metacarpal neck fractures [27–29], potentially due to the limited bone mass at the metacarpal head distal to the metacarpal neck, which restricts sufficient space for the placement of external fixation screws. The Ilizarov external mini-fixator has demonstrated excellent clinical outcomes in managing hand and foot fractures and bone defects [30–32]. Its conventional approach involves inserting 3–4 K-wires at the proximal and distal fracture sites, perpendicular to the long axis of the bone, and securing them to an external frame. However, in metacarpal neck fractures, the limited space at the distal fracture segment precludes the placement of the 3–4 parallel K-wires. Therefore, we modified the traditional Ilizarov external mini-fixator by altering the placement and orientation of the K-wires to enhance its suitability for metacarpal neck fractures and to provide greater stability.

This study aimed to compare the biomechanical stability of metacarpal neck fractures fixed with four different fixation methods: the modified Ilizarov external mini-fixator, locking plate system, crossed Kirschner wires, and intramedullary K-wires.

Materials and methods

Specimen Preparation

Due to the limited availability of fresh human specimens, 40 fresh-frozen porcine metacarpal bones from the forefeet were used as experimental models in this study. These specimens were purchased from a local meat market and immediately frozen at −20 °C after slaughter to preserve their structural integrity. Before experimentation, the specimens were thawed at room temperature, and non-weight-bearing metacarpal bones were bilaterally isolated. All soft tissues were removed from the bone surfaces, and the length and neck diameter of each metacarpal bone were measured. Only specimens with a length between 55 mm and 65 mm and a neck diameter between 14 mm and 16 mm were included in the study. (Figure 1) To simulate metacarpal neck fracture in each specimen, a standardized cut was made 5 mm proximal to the palmar edge of the metacarpal head articular cartilage using fine bone-cutting forceps with a 1 mm blade width.

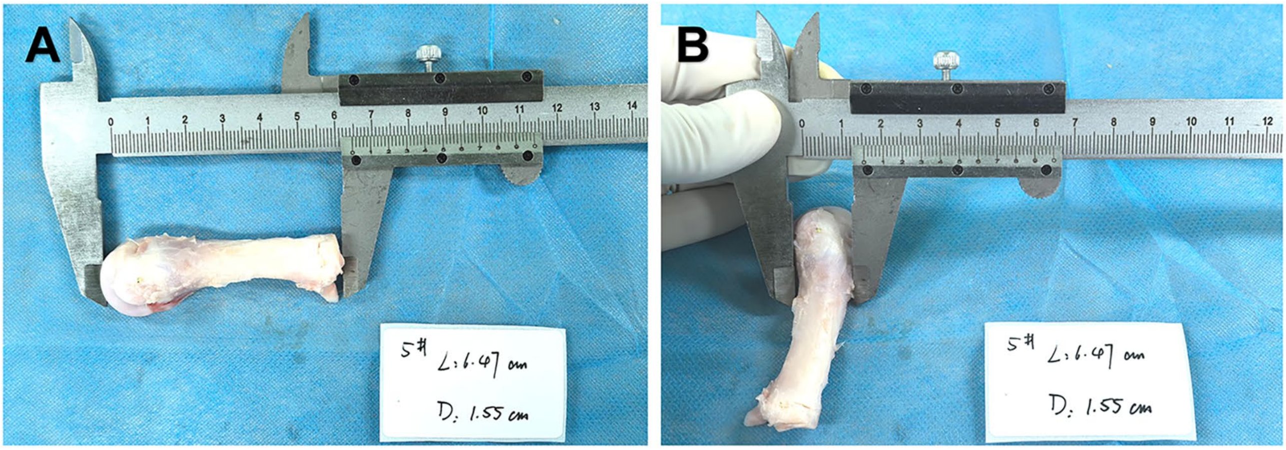

Fig. 1 Measurement of the length and diameter of porcine metacarpal bones for specimen selection. **A** Measurement of the length of the specimen. **B** Measurement of the diameter of the specimen

Fixation methods

The 40 metacarpal fracture specimens were randomly assigned to four groups, each comprising 10 specimens. Each group underwent fixation using one of the four methods. All surgical procedures were performed by the same surgeon and surgical assistants to ensure procedural consistency.

Group 1: Modified Ilizarov external mini-fixator (IEF)

In this group, fractures were first reduced and stabilized by a surgical assistant. Thereafter, two 1.5 mm K-wires were inserted retrogradely through the distal part of the metacarpal head, crossing the fracture line and penetrating the opposite proximal cortical bone. A third 1.5 mm K-wire was placed perpendicular to the long axis of the metacarpal at the metacarpal head, such that three K-wires traversed the distal fracture segment. At the proximal metacarpal shaft, three additional wires were inserted perpendicular to the long axis, alternating sides with approximately 5 mm spacing between each pair. The tails of the two crossed K-wires were bent proximally in the coronal plane until they aligned parallel to the other wires. All K-wires were bent dorsally to fit into the grooves of the external fixator ring. After securing the wires in place, the excess wire ends were trimmed.(Figure 2A).

Group 2: Retrograde crossed kirschner wires (KW)

Fractures were reduced and stabilized by the surgical assistant. Two 1.5 mm K-wires were inserted at the dorsal and lateral margins of the metacarpal head and crossed through the fracture line at the metacarpal neck and exited through the palmar cortex of the proximal fragment.(Figure 2B).

Group 3: Antegrade intramedullary Kirschner wires (IK)

Fractures were reduced and stabilized by the assistant. Two 1.5 mm K-wires were inserted into the medullary canal of the metacarpal bone, adjacent to its base, and advanced distally through the canal, crossing the fracture line and extending into the metacarpal head. The tips of the wires were positioned in the subchondral region of the metacarpal head.(Figure 2C).

Group 4: Locking plate (LP) fixation

In this group, reduction and stabilization of fractures were achieved with the help of the surgical assistant. A 2.4 mm T-shaped locking plate was secured to the dorsal surface of the metacarpal bone. Two 2.4 mm locking screws were then inserted into the metacarpal head distal to the fracture line, and three locking screws were placed proximally to ensure stability.(Figure 2D).

Biomechanical testing

A modified three-point bending test was performed to assess the biomechanical performance of the four fixation methods. To ensure secure specimen fixation and accurate testing conditions, a custom-designed fixation device was created using 3D printing technology.(Figure 3) This device consisted of a base, a specimen fixation unit, and a palmar-side support plate. The specimen fixation unit featured a cubic groove designed to securely hold the proximal end of the metacarpal specimen after fixation. Bone cement was applied to the groove, ensuring rigid specimen fixation once it solidified. The palmar-side support plate was carefully positioned 5 mm proximal to the fracture line, serving as the support point for the three-point bending test.

The base of the device featured two guiding rails, allowing the specimen fixation unit and palmar-side support plate to slide along the rails. This adjustability ensured

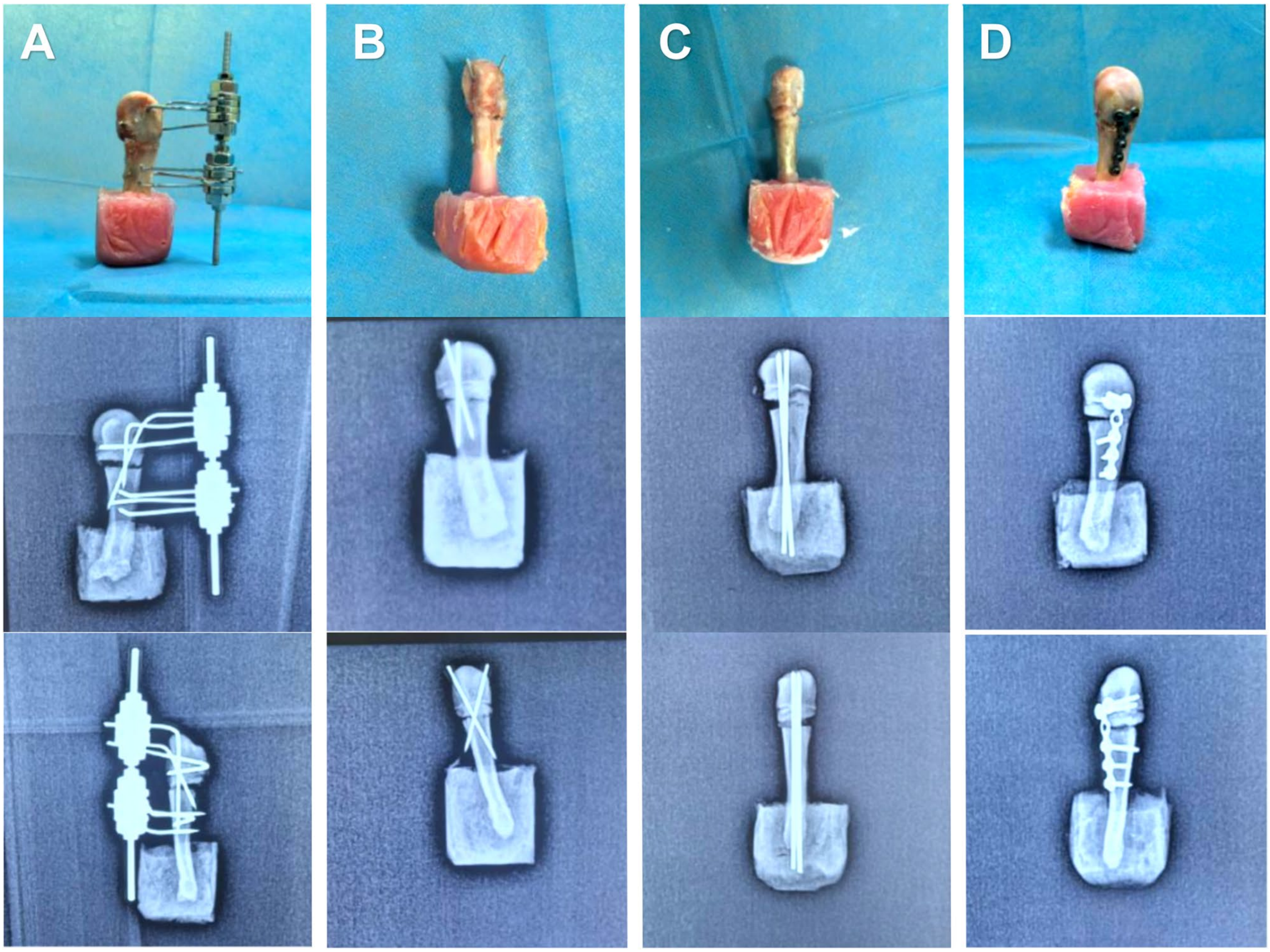

Fig. 2 Specimens were fixed using four distinct fixation methods. **A** IEF group: Ilizarov external mini-fixator. **B** KW group: Kirschner wire. **C** IK group: intra-medullary Kirschner wire. **D** LP group: locked plate

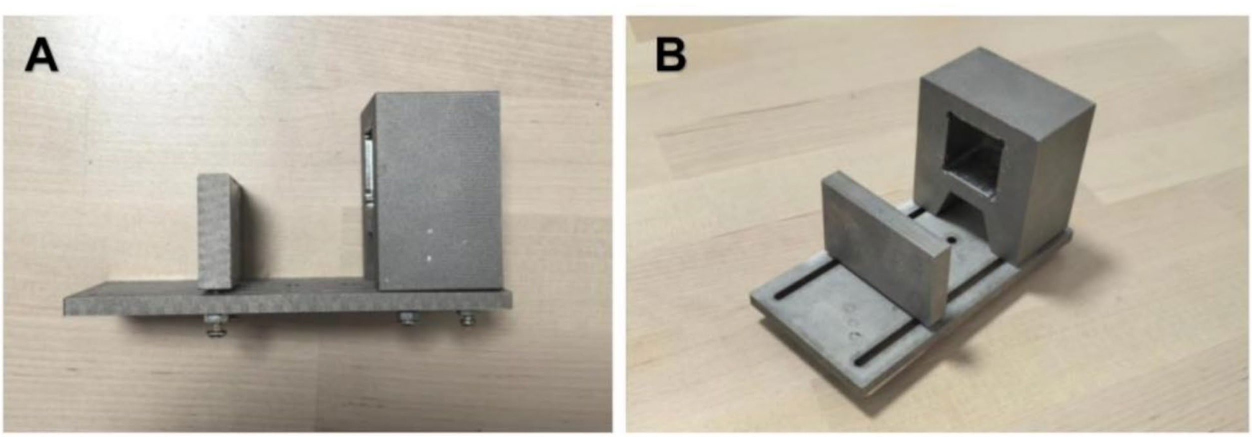

Fig. 3 Specimen fixation device created by three dimensional printing technology. **A** Side view of the specimen fixation device. **B** Oblique view of the specimen fixation device

precise specimen positioning and accurate alignment of the compression and support points.

After achieving proper alignment, the specimen fixation unit and palmar-side support plate were locked in place to prevent movement during testing. A vertical load was then applied to the dorsal area of the metacarpal head, 10 mm distal to the fracture line, at a controlled rate of 10 mm/min.(Figure 4) Force-displacement data were recorded for each specimen, and the maximum fracture force was determined. Bending stiffness was calculated based on the force-displacement data, providing a comprehensive evaluation of the mechanical stability of each fixation technique.

Statistical analysis

Kruskal–Wallis test was performed to assess differences in maximum fracture force and bending stiffness among the four fixation groups. Post hoc pairwise comparisons were conducted using Bonferroni correction to adjust for multiple testing. P-values less than 0.05, following

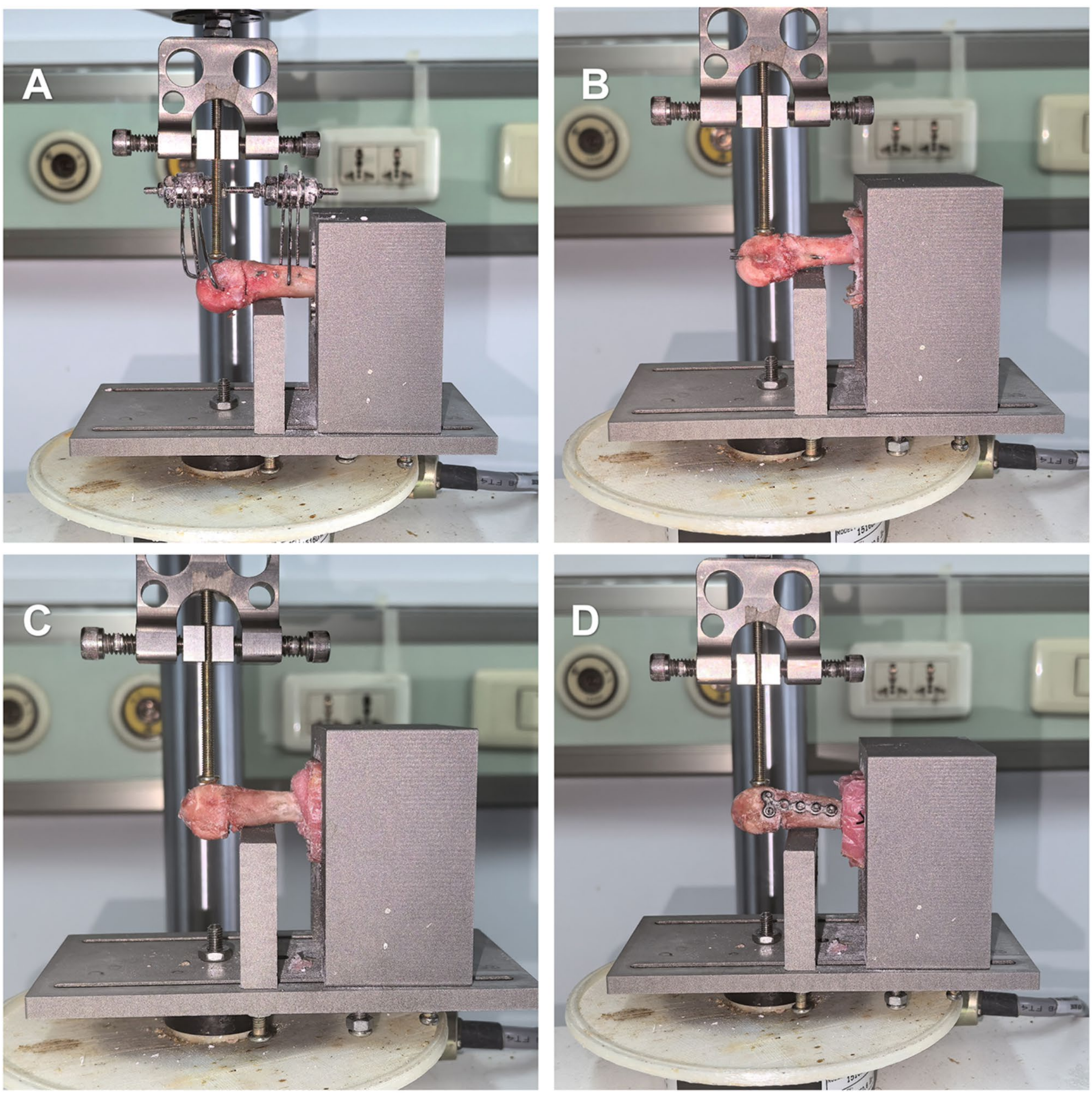

Fig. 4 Biomechanical testing setup for the four fixation methods. **A** IEF group: Ilizarov external mini-fixator. **B** KW group: Kirschner wire. **C** IK group: intramedullary Kirschner wire. **D** LP group: locked plate

Table 1 Maximum fracture force (N) of the four fixation methods for metacarpal neck fractures

Group	Sample Size	Median	IQR	MAX	MIN	*P*[a]	*P*[b]
IEF	10	160.3	55.6	209.6	125.3	< 0.001	
KW	10	91.1	23.1	120.6	69.5		0.010 (KW-IEF)
IK	10	79.8	37.8	104.9	29.6		< 0.001 (IK-IEF)
LP	10	173.5	42.6	238.8	143.9		1.000 (LP-IEF)

IEF: Ilizarov external mini-fixator **KW**: Kirschner wire

IK: intramedullary Kirschner wire **LP**: locked plate

[a]Kruskal–Wallis test for multiple independent samples

[b]Post hoc pairwise comparisons with Bonferroni adjustment

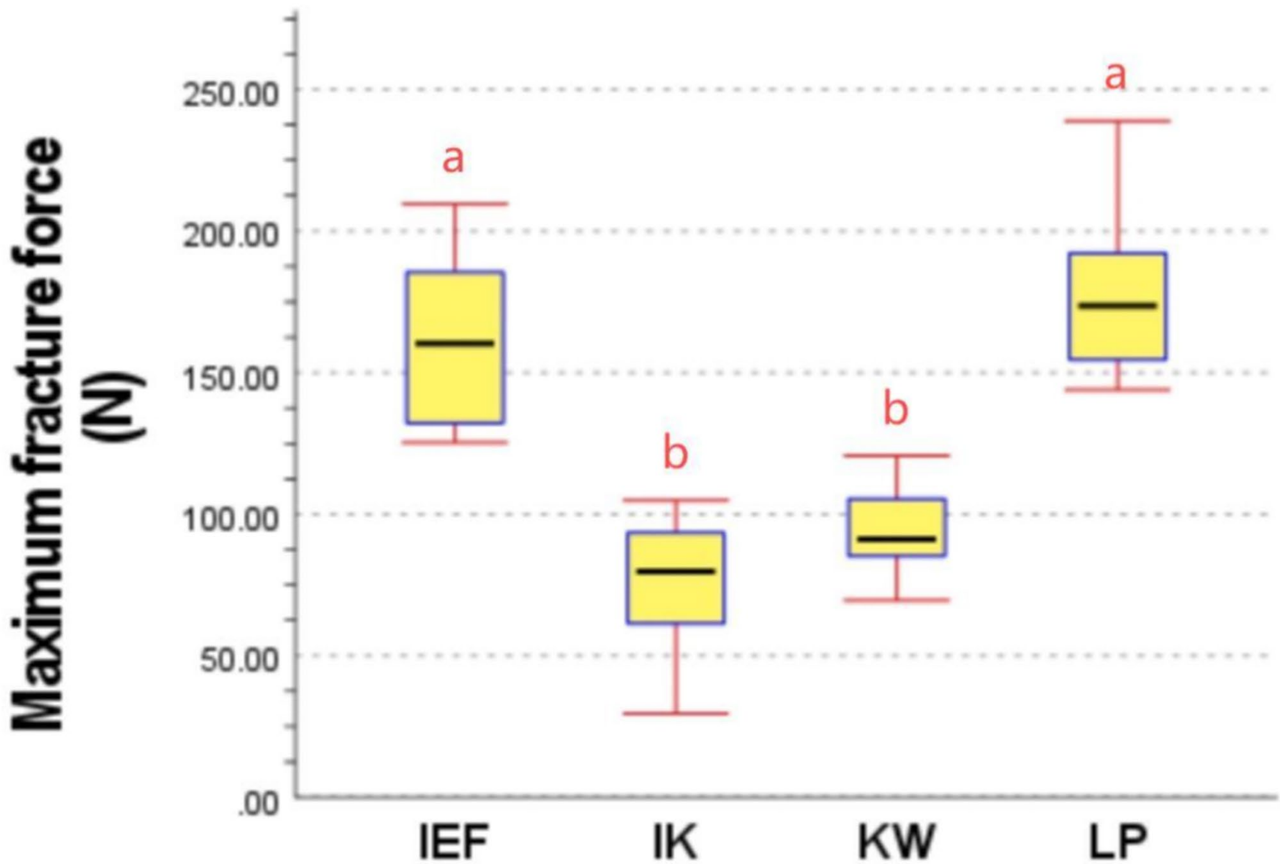

Fig. 5 Box plots representing the stiffness values of specimens fixed using the four different fixation methods. Groups with the same letters indicate no significant differences in post hoc pairwise comparisons (Bonferroni-adjusted, $P < 0.05$). **IEF**: Ilizarov external mini-fixator. **KW**: Kirschner wire. **IK**: intramedullary Kirschner wire. **LP**: locked plate

Bonferroni correction, were considered statistically significant.

Results

Maximum fracture force values

The maximum fracture force varied among the four fixation methods. The LP group exhibited the highest maximum fracture force (173.5 ± 42.6 N). The IEF group demonstrated a slightly lower maximum fracture force (160.3 ± 55.6 N) than that of the LP group; however, this difference was not statistically significant. The maximum fracture forces in the KW group (91.1 ± 23.1 N) and the IK group (79.8 ± 37.8 N) were significantly lower than those observed in the LP and IEF groups.(Table 1)(Figure 5).

Table 2 Stiffness (N/mm) of the four fixation methods for metacarpal neck fractures

Group	Sample Size	Median	IQR	MAX	MIN	P^a	P^b
IEF	10	29.5	10.4	36.6	18.2	< 0.001	
KW	10	17.2	11.3	29.1	10.7		0.035 (KW-IEF)
IK	10	18.2	13.7	27.9	8.7		0.015 (IK-IEF)
LP	10	32.9	10.4	42.2	23.1		1.000 (LP-IEF)

IEF: Ilizarov external mini-fixator **KW**: Kirschner wire

IK: intramedullary Kirschner wire **LP**: locked plate

[a]Kruskal–Wallis test for multiple independent samples

[b]Post hoc pairwise comparisons with Bonferroni adjustment

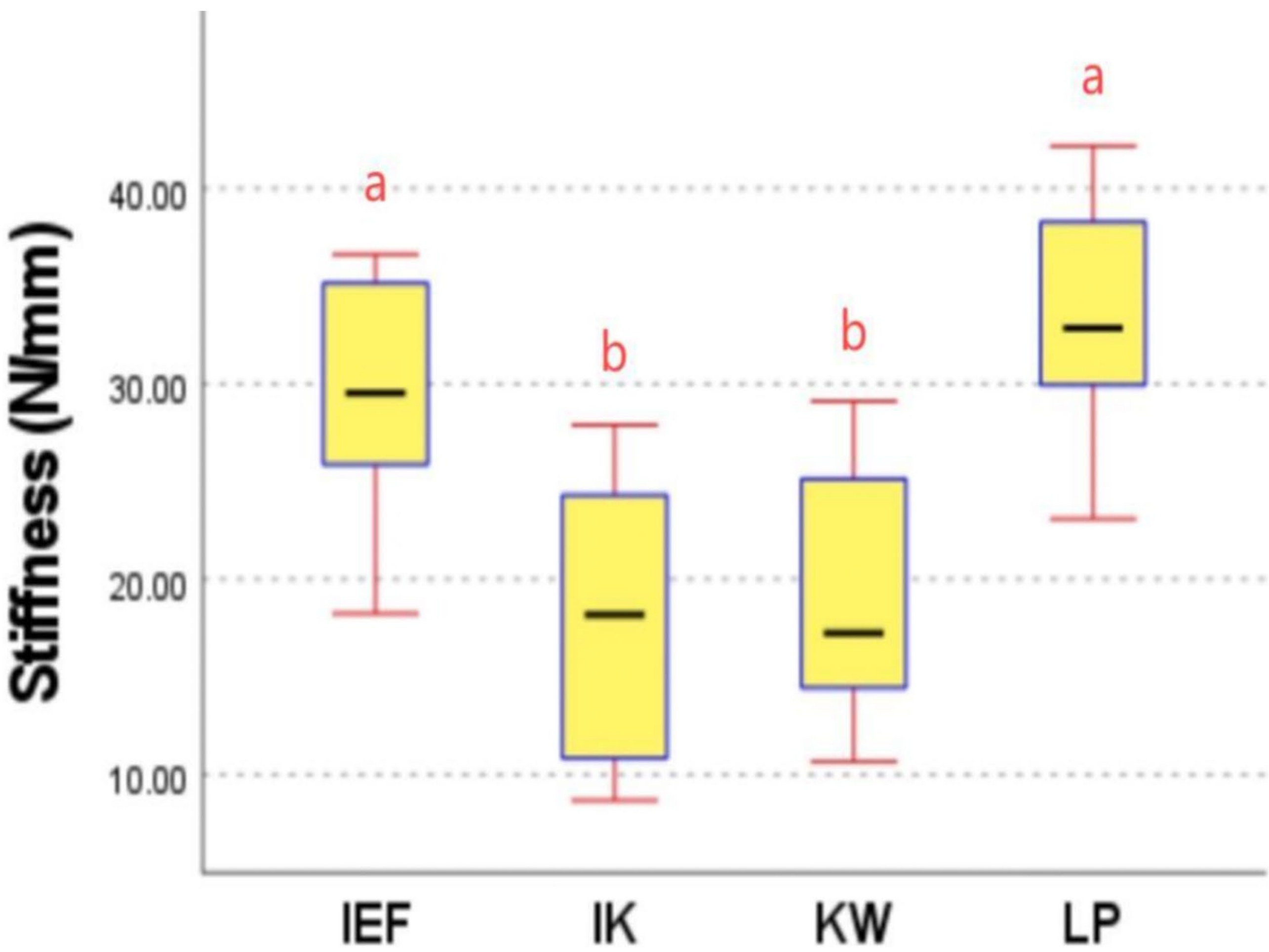

Fig. 6 Box plots representing the maximum fracture force values of specimens fixed using the four different fixation methods. Groups with the same letters indicate no significant differences in post hoc pairwise comparisons (Bonferroni-adjusted, $P < 0.05$). **IEF**: Ilizarov external mini-fixator. **KW**: Kirschner wire. **IK**: intramedullary Kirschner wire. **LP**: locked plate

Stiffness values

The LP group demonstrated the highest stiffness (32.9 ± 10.4 N/mm) among the four groups. The median stiffness in the IEF group (29.5 ± 10.4 N/mm) was lower than that of the LP group but significantly higher than those of the KW (17.2 ± 11.3 N/mm) and IK (18.2 ± 13.7 N/mm) groups. However, no statistically significant difference in stiffness was observed between the LP and IEF groups.(Table 2)(Figure 6).

Discussion

Metacarpal neck fractures are among the most common hand fractures. While most cases can be managed conservatively, surgical intervention is indicated in fractures with significant angular deformities, shortening, or rotational malalignment. Common surgical fixation methods include K-wire fixation, intramedullary screw fixation, plate fixation, and external fixation. Among these techniques, K-wire fixation is the most widely used method for hand fractures, encompassing retrograde cross K-wire fixation, antegrade intramedullary K-wire fixation, and transverse K-wire fixation [12]. Cross pinning and transverse pinning are relatively simple to perform, minimally invasive, with a short learning curve; however, they offer limited mechanical stability and are associated with a higher incidence of complications [16, 18, 19]. Antegrade intramedullary K-wire fixation, although minimally invasive, presents a longer learning curve and carries risks such as joint surface injury and damage to the dorsal branch of the ulnar nerve [33]. Locking plate systems provide greater fixation stability but require extensive soft tissue dissection, potentially leading to complications such as joint stiffness, tendon injury, and bone nonunion. These limitations have contributed to a gradual decline in the use of locking plates, particularly with the increasing application of novel minimally invasive techniques [26].

External fixation has been widely used in hand fracture management [34–35]. Although initially indicated for open fractures and bone defects, recent studies have demonstrated favorable outcomes in the treatment of closed metacarpophalangeal fractures [36–38]. Compared with K-wire fixation, external fixation offers similar ease of application, minimizes soft tissue injury, and provides greater stability. Unlike locking plates, external fixation does not require a skin incision, minimizes trauma, and obviates the need for a second surgery for implant removal. To ensure secured fixation, adequate placement of screws or K-wires at both sides of the fracture is essential, regardless of the type of external fixator used (traditional unilateral external fixator or Ilizarov external mini-fixator). Typically, the configuration for treating metacarpal and phalangeal fractures with a mini Ilizarov external fixator involves inserting 3 to 4 Kirschner wires perpendicularly to the long axis of the bone at both the proximal and distal parts of the fracture line. However, in cases of metacarpal neck fractures, the distal fragment is relatively small, making it difficult to insert 3 to 4 parallel Kirschner wires. Even when insertion is possible, the inter-wire distance is often too narrow to accommodate the fixation grooves on the external fixator. To address this issue, we first insert two Kirschner wires retrogradely and in a crossed manner into the metacarpal head, followed by the insertion of one Kirschner wire perpendicular to the long axis of the metacarpal. When connecting the external fixator, the tails of the two crossed Kirschner wires are first bent coronally towards the proximal side until they are parallel to the other Kirschner wires, and then all the Kirschner wires are bent dorsally to be connected and fixed onto the external fixator. In this manner, the three Kirschner wires at the distal part can be staggered, and the adjustment of the bending positions can align with the grooves on the external fixator, facilitating the placement of wires at the distal part. Meanwhile, two Kirschner wires placed in a crosswise manner pass through the fracture line and the contralateral cortex, which theoretically can further enhance the stability of the fracture ends. Given the lack of previous evaluation on the effectiveness of this modified technique, this study was conducted to assess its biomechanical performance.

Due to the limited availability of fresh human metacarpal specimens, studies have employed artificial bone models [39–41] or porcine metacarpal bones [42, 43]. In this study, non-weight-bearing metacarpals from porcine forefeet were selected as experimental specimens. These specimens closely model human metacarpals in length and diameter and are readily available. To evaluate the biomechanical performance of the different fixation methods, we employed a modified three-point bending test. While in vivo loading of the metacarpals is complex, involving intricate muscle and ligament forces difficult to replicate in vitro, the three-point bending test effectively simulates the primary forces responsible for metacarpal neck fractures [42].

This study evaluated two primary biomechanical variables: maximum fracture force and stiffness. Maximum fracture force represents the peak strength of the fixation device, while stiffness reflects its resistance to deformation. The result revealed that the LP group exhibited the highest maximum fracture force and stiffness, indicating superior stability of plate fixation, consistent with previous reports in basic and clinical studies [13, 17, 26, 42, 43]. The IEF group demonstrated significantly higher maximum fracture force and stiffness than the KW and IK groups, suggesting that the modified Ilizarov external mini-fixator offers greater mechanical stability than K-wire fixation. This improved stability of the IEF group can be attributed to its load-sharing mechanism. While the KW and IK groups rely entirely on two K-wires to bear the load, the IEF group distributes the load between the two crossed K-wires and the external fixator frame, which provides greater stability. Although the IEF group exhibited slightly lower values for maximum fracture force and stiffness than the LP group, these differences were not statistically significant. This slight difference may be attributed to the mechanical advantages offered by the two fixation systems. The locking plate's direct contact with the bone and short lever arm provides superior mechanical advantages. In contrast, the external fixator has a longer lever arm, and its connection to the bone through K-wires introduces some elastic loss, leading to slightly reduced stability. Despite these differences, the modified Ilizarov external fixator offers sufficient stability for metacarpal neck fractures, obviating the need for postoperative supportive fixation such as splints. Similar to locking plate fixation, this modified device enables early joint mobilization, potentially facilitating early functional recovery and reducing the risk of complications such as joint adhesion.

The distance between the external fixator and the bone is also one of the factors influencing the stability of fixation. Generally, the closer the external fixator is to the bone, the smaller its lever arm is, and the stronger the stability will be; conversely, the same holds true. In this study, for the convenience of experimental operation, the distance between the external fixator and the bone was not strictly controlled, and the distance of each specimen was approximately 2 cm to 2.5 cm. In the experiment, the two smallest stiffness values in the IEF group were indeed measured on the two specimens with the largest distance from the external fixator to the bone, which further substantiated the correlation between the distance from the external fixator to the bone and the stability of fixation. In clinical applications, the distance from the external fixator to the bone is generally smaller than that in this experiment. Theoretically, its stability would be better.

This study has some limitations. First, porcine metacarpals, although similar in length and diameter to human metacarpals, differ in bone density and trabecular orientation, potentially limiting the generalization of these findings to human models. Second, this in vitro study does not fully replicate the complex in vivo loading environment, which includes forces from muscle, ligament, and joint mechanics. Consequently, the three-point bending test simulated primarily bending forces inducing angular deformities but did not account for axial or rotational loads, underscoring the need for further investigation into these loading conditions to provide a more comprehensive assessment.

Conclusion

The modified Ilizarov external mini-fixator provides significantly greater mechanical stability than retrograde cross K-wire fixation and antegrade intramedullary K-wire fixation for metacarpal neck fractures. Its biomechanical performance is comparable to that of the locking plate system. This modified technique effectively combines the simplicity and minimally invasive advantages of K-wire fixation with the superior stability of locking plates, allowing for early functional rehabilitation without the need for additional supportive fixation. This advantage potentially accelerates recovery and reduces the risk of postoperative complications.

Abbreviations

K-wires	Kirschner wires
IQR	Interquartile range

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Author contributions

This study was initiated and developed by CX and ZL. The experiment was designed by CX and conducted by CX, YD, and ZY. CX and YD were responsible for collecting and organizing experimental data and conducting statistical analysis. The preliminary version of the study was authored by CX, while the final version was carefully examined and endorsed by all the authors.

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Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study has been approved by the Ethics Committee of the 960th Hospital of PLA (No 2023-032).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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