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RESEARCH ARTICLE

Title: Biomechanics of Plum-Blossom Nail and Bone Cement in Porcine Femoral Metastasis Models at Different Sites

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Abstract: This study aims to evaluate the mechanical strength and fixation performance of clover-shaped intramedullary nails combined with bone cement in porcine models of femoral metastatic tumors located at the subtrochanteric, midshaft, and supracondylar regions. Thirty-six pairs of fresh porcine femurs were used, with nine pairs assigned to a control group and the remaining divided into three metastatic tumor model groups according to anatomical location. In each model group, the right femurs were unfixed, while the left femurs were fixed. Each pair was further subdivided for testing compressive strength, torsional strength, and bending strength. The fixed femurs showed significantly greater mechanical strength than the unfixed models in all anatomical locations. In fixed models, compressive strength reached 71.0%, 80.6%, and 30.7% of control values in the subtrochanteric, midshaft, and supracondylar groups, respectively. Torsional strength reached 41.2%, 50.7%, and 52.0%, while bending strength reached 98.0%, 64.4%, and 40.0% of the control values for the same locations. These findings indicate that the fixation method provides effective biomechanical support in the subtrochanteric and midshaft regions but offers only moderate reinforcement in the supracondylar region. Moreover, our fixation approach may be suitable for stabilizing femoral metastatic lesions in specific anatomical sites.

Keywords: Femoral metastatic tumor; Plum-blossom intramedullary nail; Bone cement; Biomechanics

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1. Introduction

Bone tissue is the third most common site of distant metastasis of malignant tumors, following the lungs and liver [1]. Statistics show that the incidence of bone metastases is 35 to 40 times higher than that of primary malignant bone tumors [2]. Bone metastasis is one of the major causes of cancer-related pain. Complications such as pathological fractures, spinal cord compression, hypercalcemia, and bone marrow failure accelerate disease progression and severely affect the quality of life of cancer patients. In the past decade, with the continuous improvement of comprehensive medical treatment, the survival time of patients with malignant tumors has significantly increased. From 2011 to 2016, the 5-year relative survival rate for malignant tumors in China was 40.5% [3]. However, the incidence of distant metastases has also increased significantly [4].

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Lung cancer, breast cancer, prostate cancer, thyroid cancer, and kidney cancer are the malignant tumors most likely to metastasize to bone, accounting for over 80% of bone metastasis cases [5]. Wu Wenjuan [6] analyzed 594 cases of bone metastases at the Third Hospital of Hebei Medical University, among which 132 cases involved the femur, accounting for 22.2%. Metastases to the femur make up as much as 65.1% of limb bone metastases [7]. Because the femur bears the greatest load during standing and walking, the incidence of pathological fractures in the femur accounts for 61% of all long bones, significantly higher than in other locations [5]. Therefore, research on femoral metastases should be given sufficient attention.

Femoral metastases most commonly occur in the proximal femur, but metastases to the femoral shaft carry the highest risk of pathological fracture. Sun Tao [8] found that the highest proportion (63.6%) of femoral metastases occurred in the proximal femur. This differs from primary malignant tumors of the femur, which are more common in the distal femur [6]. Traditional views suggest that proximal femoral metastases have both the highest incidence and the highest risk of pathological fracture [9]. However, Sun Tao [8] reported that the overall pathological fracture rate in femoral metastases is 27.3%, with a notably high rate of 42.4% in the femoral shaft, significantly higher than the 23.4% observed in the proximal femur. This indicates that the risk of pathological fractures in femoral shaft metastases exceeds that in proximal metastases, which deserves greater attention from orthopedic surgeons. Active surgical intervention is needed to prevent pathological fractures of the femoral shaft.

There have been reports of using minimally invasive closed intramedullary nailing for the fixation of femoral shaft metastases [10], with favorable outcomes. The advantages include minimal trauma, rapid postoperative recovery, and significant pain relief from bone metastasis. However, its disadvantages include relatively poor stability at the fracture site, persistent limb pain, and potential locking screw breakage of the intramedullary nail over time. If combined with bone cement, better fixation and pain relief can be achieved [11,12].

In this study, a femoral metastasis model in pigs was stabilized using a petal-shaped intramedullary nail combined with bone cement to test its fixation strength, and to verify whether this surgical method can address the aforementioned issues. For patients with advanced cancer and femoral metastases who cannot tolerate or refuse open surgery, this offers a minimally invasive closed surgical fixation option.

2. Materials and methods

2.1 Experimental materials

The model specimens were taken from the femurs of the hind limbs of 0.8–1.0-year-old Large White pigs (approximate body weight: 200–250 kg), totaling 36 pairs. Mendec bone cement (main component: polymethyl methacrylate; medium viscosity) and petal-shaped intramedullary nails DA/10×400 (manufactured by Tianjin Jinxingda Industrial Co., Ltd., registration number: National Medical Device Registration 20153460335) were used.

2.2 Experimental instruments

An electro-hydraulic universal testing machine (WE-1000B model, Jinan Zhongluchang Testing Machine Manufacturing Co., Ltd.), an RFP-09 intelligent force gauge (Hengle Instruments), and a vernier caliper (Model: 0–150 mm, Shanghai Measuring Tools, measuring range: 0–150 mm, reading value: 0.02 mm) were used.

3. Experimental methods

This work was supported by the Department of Finance of Inner Mongolia Autonomous Region and received ethical approval from the Medical Ethics Committee of Inner Mongolia Medical University.

3.1 Experimental grouping

Control Group: Nine pairs (18 samples) of healthy adult porcine femurs were used as the control group. These were randomly assigned to three test subgroups: Test Group ①, ②, and ③, with six femurs in each subgroup. All samples were derived from three pigs, with each pair of femurs obtained from the same animal.

Group 1: Nine pairs (18 samples) of subtrochanteric femoral bone metastasis models were established. Among them, 9 femurs were left unfixed and divided into three subgroups: Test Group ①, ②, and ③, with three samples per subgroup. The other 9 femurs were fixed and equally divided into the same three subgroups. (Note: To minimize variability, paired femurs from the same animal were used such that the right femur was constructed into an unfixed model and the left femur into a fixed model, undergoing the same mechanical testing. This pairing and testing method was consistent across Test Groups ①, ②, and ③.)

Group 2: Nine pairs (18 samples) of mid-diaphyseal femoral bone metastasis models were established. Similarly, 9 unfixed samples were divided into Test Groups ①, ②, and ③ (n = 3 per group), and 9 fixed samples were divided likewise. (Note: The grouping and paired testing methodology were identical to those used in Group 1.)

Group 3: Nine pairs (18 samples) of supracondylar femoral bone metastasis models were established. Again, 9 unfixed and 9 fixed femurs were divided into Test Groups ①, ②, and ③, with 3 samples per group. (Note: The same

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pairing and group assignment method as described in Group 1 was employed for consistency.)

3.2 Model preparation

3.2.1 Establishment of Femoral Bone Metastasis Destruction Models

Bone metastasis destruction models were established at different sites of the femoral shaft. The lesions were created on the posterior side of the femur (i.e., the compressive side), including 18 subtrochanteric sites, 18 mid-diaphyseal sites, and 18 supracondylar sites.

The standard for bone defect creation was a longitudinal length of 6 cm and a circumferential defect encompassing two-thirds of the bone's perimeter, in accordance with the Expert Consensus on Surgical Treatment of Bone Metastases, which recommends surgical intervention when the circumferential cortical defect exceeds two-thirds in long bones [13].

A vernier caliper was used to measure cortical thickness at the defect site. Models were considered qualified if the difference in cortical thickness between the same sites on contralateral femurs was within ±1.5 mm.

3.2.2 Fixation of Femoral Bone Metastasis Destruction Models

Paired femurs from the same pig were used to establish bone destruction models at corresponding anatomical sites. The right femur was left unfixed, while the left femur was fixed using a cloverleaf-shaped intramedullary nail combined with bone cement. Both femurs from the same pair were allocated to the same testing subgroup to minimize experimental variability.

Following the piriformis fossa approach, the intramedullary canal was opened at the piriformis fossa. The bone marrow contents were thoroughly removed, and the medullary cavity was flushed clean to ensure complete clearance of marrow tissue.

A cloverleaf-shaped intramedullary nail with a diameter of 10 mm was cut to match the length of the medullary cavity. Bone cement was mixed to a stringy consistency and injected into the medullary canal using a bone cement gun. The intramedullary nail was then inserted. After the cement reached room temperature and solidified, the specimen was stored at 18 °C for 48 hours before mechanical testing.

A total of 27 fixed femurs (left side) were prepared, including 9 at the subtrochanteric site, 9 at the mid-diaphyseal site, and 9 at the supracondylar site.

3.2.3 Biomechanical Testing of the Femur

An electro-hydraulic universal testing machine was used to assess compressive and bending strength. Each femur was positioned so that its proximal and distal ends were in full contact with the compression fixtures. A preload was applied at a speed of 10 mm/min until a force of 100 N was reached to eliminate creep and ensure complete fixation, thereby preventing slippage and data artifacts. After fixation, the load was zeroed.

Compression loading was then applied at a constant speed of 10 mm/min. The force accuracy was ±0.01 N and the displacement accuracy was ±0.05 mm. Throughout testing, femoral deformation was closely observed, and force-displacement data were recorded continuously. Loading was maintained until femoral fracture occurred, and the fracture load and morphological changes were documented. All tests were conducted at room temperature to minimize error.

Torsional strength was assessed using an RFP-09 intelligent force measuring device. The proximal and distal ends of the femur were securely clamped, and the femoral longitudinal axis was aligned with the rotation axis of the instrument. Torsional loading was applied at a rate of 100°/min. The torque accuracy was ±0.01 N·m. The femur was monitored continuously for signs of deformation and failure. Torque-displacement data were recorded until fracture occurred, and the corresponding torque values and fracture characteristics were noted. All samples were maintained at room temperature throughout testing to reduce variability.

3.3 Statistical analysis of experimental results

All measurement data were expressed as mean ± standard deviation (±s). Statistical analyses were performed using SPSS software version 23.0 (IBM Corp., USA). For comparisons between two groups, the student's t-test was applied. One-way analysis of variance (ANOVA) was used for comparisons among multiple groups. A P-value of <0.05 was considered statistically significant.

Prior to intergroup comparisons, homogeneity of variance was tested within each group for all indicators. Subsequently, homogeneity of variance between the experimental and control groups was assessed. All data were analyzed using SPSS version 20.0. In all statistical tests, a P-value <0.05 indicated a statistically significant difference.

4. Results

4.1 Femoral metastatic tumormModeling results

4.1.1 Subtrochanteric femoral metastatic tumor model:

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Fig. (1). Porcine femur and cloverleaf intramedullary nail, subtrochanteric bone defect model with 2/3 circumferential destruction and 5 cm length.

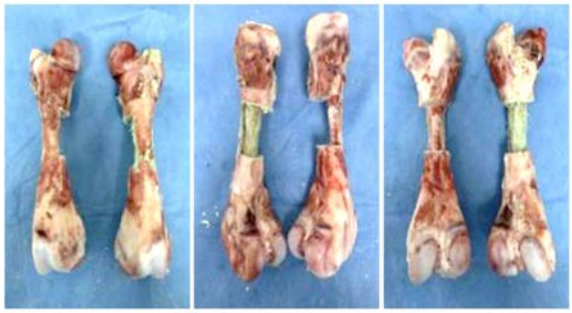


Fig. (2). Anteroposterior and lateral images of the subtrochanteric bone defect model fixed with a cloverleaf intramedullary nail and bone cement.

4.1.2 Midshaft femoral metastatic tumor model:



Fig. (3). Porcine femur and cloverleaf intramedullary nail; midshaft bone defect model with 2/3 circumferential destruction and 5 cm length.



Fig. (4). Anteroposterior and lateral images of the midshaft bone defect model fixed with a cloverleaf intramedullary nail and bone cement.

4.1.3 Supracondylar femoral metastatic tumor model:

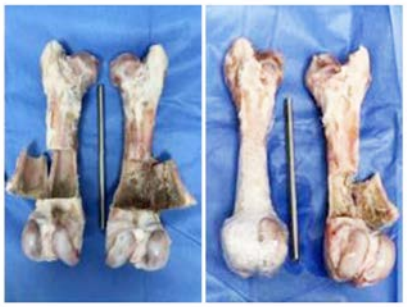


Fig. (5). Porcine femur and cloverleaf intramedullary nail; supracondylar bone defect model with 2/3 circumferential destruction and 5 cm length)



Fig. (6). Anteroposterior and lateral images of the supracondylar bone defect model fixed with a cloverleaf intramedullary nail and bone cement.

4.2 Femoral metastatic tumor testing results

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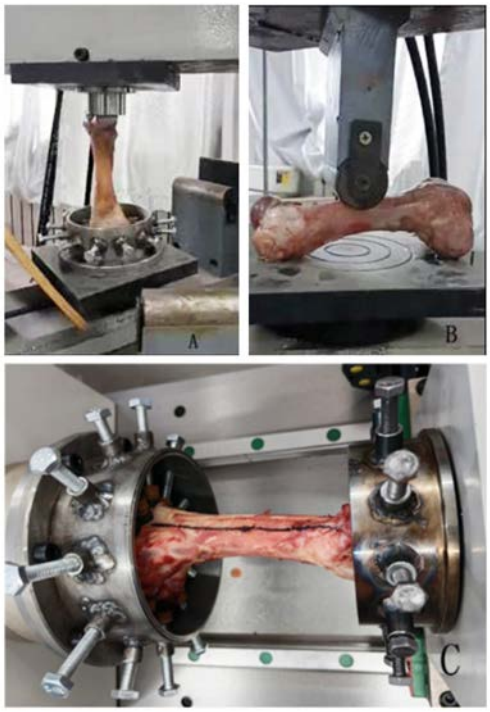


Fig. (7). Mechanical testing of porcine femoral bone defect models: A. Compression resistance test; B. Bending resistance test; C. Torsional resistance test.

4.2.1 Compression Resistance Results and Evaluation of Femoral Metastatic Tumor Models

Table 1. Comparison of compression resistance values in femoral metastatic tumor models ($\bar{x} \pm s$)

Group	Sample Size (n)	Maximum Compression Resistance (KN)	Percentage of Control Group's Maximum Compression Resistance
Control (Healthy)	6(3pairs)	12.10 ± 0.29	100%
Subtrochanteric Unfixed	3	2.31 ± 0.81	19.1%
Subtrochanteric Fxed	3	8.58 ± 0.85	71%
Midshaft Unfixed	3	2.37 ± 0.06	19.6%
Midshaft Fixed	3	9.75 ± 0.79	80.6%
Supracondylar Unfixed	3	2.33 ± 0.03	19.3%
Supracondylar Fixed	3	3.71 ± 0.20	30.7%

Table 2. Comparison of compression resistance values (KN) between unfixed and fixed groups in three different femoral metastatic tumor models ($\bar{x} \pm s$)

Group	Unfixed Group	Fixed Group	P-value
Subtrochanteric Metastatic Model	2.31 ± 0.81	8.58 ± 0.85	<0.001
Midshaft Metastatic Model	2.37 ± 0.06	9.75 ± 0.79	<0.01
Supracondylar Metastatic Model	2.33 ± 0.03	3.71 ± 0.20	<0.01

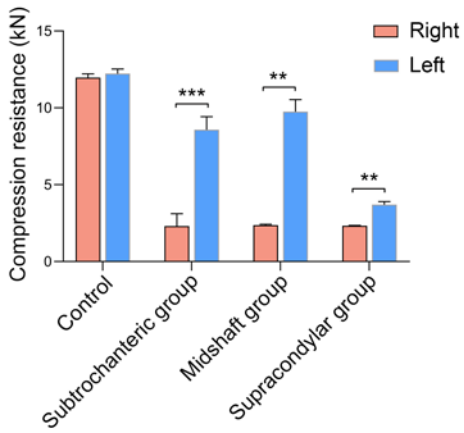


Fig. (8). Effect of fixation on the mechanical properties of different metastatic bone models. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, $^{****}P < 0.0001$.

The normal pig femur (control group) could withstand a pressure of 12.10 ± 0.29 kN. Considering that 1 kN is approximately equivalent to the gravitational force of a 102 kg object, this corresponds to the gravitational force of a 1200 kg object, which is five times the body weight of the pig (250 kg). In the unfixed groups of femoral shaft

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metastasis models at three different anatomical locations, the maximum pressure resistance was less than 20% of that of the control group (approximately equivalent to the gravitational force of a 240 kg object). These models could not support the pig's own body weight of 250 kg and were prone to fracture, indicating that unfixed models in femoral metastasis modeling are highly susceptible to fractures. In contrast, comparison with the fixed groups effectively evaluates the fixation performance.

In the fixed groups, the subtrochanteric fixation group could withstand up to 71% of the control group's maximum pressure resistance (approximately equivalent to the gravitational force of an 850 kg object), the midshaft fixation group reached 80.6% (approximately equivalent to 970 kg), and the supracondylar fixation group reached 30.7% (approximately equivalent to 370 kg). Among these, the subtrochanteric and midshaft fixation groups achieved stable fixation effects, while the fixation effect of the supracondylar group was moderate.

4.2.2 Torsional resistance results and evaluation of femoral metastatic tumor models

Table 3. Comparison of compression resistance values in femoral metastatic tumor models ($\bar{x}\pm s$)

Group	Sample Size (n)	Maximum Torsional Resistance (N/m)	Percentage of Control Group's Maximum Torsional Resistance
Control (Healthy)	6	74.86± 7.30	100%
Subtrochanteric Unfixed	3	9.61± 1.68	12.8%
Subtrochanteric Fixed	3	30.87± 2.58	41.2%
Midshaft Unfixed	3	11.46± 2.02	15.3%
Midshaft Fixed	3	37.96± 4.48	50.7%
Supracondylar Unfixed	3	9.04± 2.01	12.1%
Supracondylar Fixed	3	38.96± 4.71	52.04%

Table 4. Comparison of torsional resistance values (N/m) between unfixed and fixed groups in three different femoral metastatic tumor models ($\bar{x}\pm s$)

Group	Unfixed	Fixed Group	P-value
Subtrochanteric Metastatic Model	9.61±1.68	30.87±2.58	<0.001
Midshaft Metastatic Model	11.46±2.02	37.96±4.48	<0.01
Supracondylar Metastatic Model	9.04±2.01	38.96±4.71	<0.01

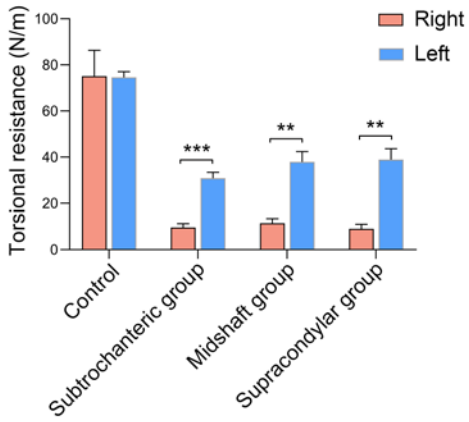


Fig. (9). The effect of fixation on mechanical properties of different metastatic bone models. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, $^{****}P < 0.0001$.

The normal pig femur (control group) could withstand a torque of 74.86 ± 7.30 N/m. In the unfixed groups of femoral shaft metastasis models at three different anatomical locations, the torque resistance was less than 16% of the control group's maximum torque capacity. In the fixed groups, the torque resistance reached only 40% to 50% of the control group's maximum value. Although the torque resistance was significantly improved compared to the unfixed models, it remained generally inferior to that of the control group. This indicates that even with full adhesion between bone cement and the medullary canal wall, the achieved torsional strength is still limited.

4.2.3 Results and evaluation of bending resistance in femoral metastatic tumor models

Table 5. Comparison of Bending Resistance Values in Femoral Metastatic Tumor Models($\bar{x}\pm s$)

Group	Sample	Maximum	Percentage of

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	Size (n)	Bending Resistance (KN)	Control Group's Maximum Bending Resistance
Control (Healthy)	6	4.47±0.26	100%
Subtrochanteric Unfixed	3	1.06±0.08	23.7%
Subtrochanteric Fixed	3	4.47±0.06	98%
Midshaft Unfixed	3	0.59±0.11	13.2%
Midshaft Fixed	3	2.88±0.55	64.4%
Supracondylar Unfixed	3	0.59±0.02	13.2%
Supracondylar Fixed	3	1.79±0.08	40.04%

Table 6. Comparison of Bending Resistance Values Between Unfixed and Fixed Groups in Three Different Femoral Metastatic Tumor Models($\bar{x}\pm s$)

Group	Unfixed Group	Fixed Group	P-value
Subtrochanteric Metastatic Model	1.06±0.08	4.47±0.06	<0.0001
Midshaft Metastatic Model	0.59±0.11	2.88±0.55	<0.05
Supracondylar Metastatic Model	0.59±0.02	1.79±0.08	<0.001

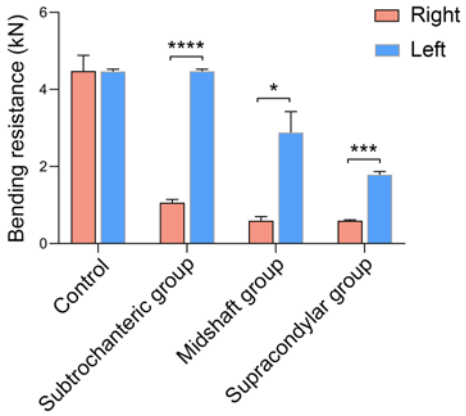


Fig. (10). The effect of fixation on the mechanical properties of different bone metastasis models.*P < 0.05, **P < 0.01, ***P < 0.001, ****P < 0.0001.

The normal pig femur (control group) could withstand a bending force of 4.47 ± 0.26 kN, equivalent to the gravitational force of approximately 450 kg, or 1.8 times the pig's own body weight of 250 kg. In the unfixed femoral shaft metastasis models at three different anatomical locations, the intertrochanteric group could withstand 23.7% of the control group's maximum bending force (approximately 106 kg), while the midshaft and supracondylar groups could only withstand 13.2% of the control value (approximately 60 kg). This suggests that (1) the bone quality in the intertrochanteric region is stronger than in the midshaft and supracondylar regions, and (2) insufficient bending resistance more readily leads to fractures.

In the fixed groups, the intertrochanteric group achieved 98% of the control group's maximum bending resistance (approximately 441 kg), the midshaft group reached 64.4% (approximately 290 kg), and the supracondylar group reached 40.04% (approximately 180 kg). Among them, the intertrochanteric group demonstrated excellent fixation results, the midshaft group achieved firm fixation, and the supracondylar group showed only moderate fixation performance.

4.2.4 Comprehensive evaluation of fixation effect in femoral diaphyseal metastasis models at three different locations

Based on the mechanical testing results of the femoral defect models in pigs—fixed using the combination of a plum-blossom-shaped intramedullary nail and bone cement—the intertrochanteric and midshaft models achieved

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compressive resistance ranging from 800 to 1000 kg and bending resistance ranging from 300 to 450 kg, indicating excellent fixation outcomes. However, the torsional resistance reached only 40%–50% of the maximum torque resistance observed in the control group, suggesting moderate effectiveness in torsional stability. Overall, the fixation performance was rated as good.

n the supracondylar femoral defect model, compressive resistance reached 370 kg and bending resistance reached 180 kg, both showing a significant decrease compared to the intertrochanteric and midshaft models, indicating a decline in fixation effectiveness. Torsional resistance remained at 40%–50% of the control group's maximum, consistent with the other two models, and was therefore also rated as moderate. Overall, the fixation performance in the supracondylar model was considered moderate.

Table 7. Comprehensive evaluation of fixation effects in femoral diaphyseal metastasis models at three different locations

Group	Excellent	Good	Fair	Poor
Subtrochanteric femoral metastasis model		√		
Midshaft femoral metastasis model		√		
Supracondylar femoral metastasis model			√	

5. Discussion

The aim of this study is to explore a minimally invasive surgical method for the treatment of femoral shaft metastases in patients with advanced cancer. Most patients with femoral bone metastases in the late stage of cancer have a relatively short survival time. Once pathological fractures occur, prolonged bed rest will significantly shorten the patient's survival and cause considerable suffering [14–15]. Therefore, both preventive surgery before pathological fracture and therapeutic surgery after fracture are necessary for patients with femoral metastases [16].

Although radical surgery can completely remove the lesion, provide stronger fixation, and offer better pain relief, patients must endure the risk of significant surgical trauma. Most patients with advanced cancer have undergone surgery, chemotherapy, radiotherapy, etc., and are no longer physically able to tolerate highly invasive operations. Moreover, the recovery time after major surgery is relatively long, and the actual benefit to the patient is limited. In reality, patients and their families often find it difficult to accept such surgery and tend to abandon treatment. To ensure better treatment and pain relief for these patients, it is a pressing challenge for orthopedic surgeons to find a minimally invasive surgical method.

Minimally invasive surgery must meet the following criteria: minimal surgical trauma, reliable fixation, rapid postoperative recovery of limb function, significant pain relief, and no interference from internal fixation devices with postoperative radiotherapy or ablation of femoral shaft metastases [17–18].

Experiments have shown that the unique hollow and side-grooved structure of the petal-shaped intramedullary nail facilitates the formation of an integrated construct with bone cement both inside and outside the nail, which completely encloses the nail and forms a strong composite. In the early phase of its working time, bone cement is flowable and can enter the hollow interior of the petal-shaped nail and flow through the side grooves into the lesion and the medullary cavity. The bone cement fills the femoral canal, conforms to the shape of the canal, and after thorough removal of bone marrow, it enters the trabecular spaces, forming a tight bond with bone to achieve strong fixation. Moreover, in the later stage of its working time, bone cement generates instant high temperature, which can kill cancer cells and thereby relieve pain and reduce the risk of cancer cell dissemination caused by surgery [19–22].

This fixation method mainly relies on bone cement bonding the petal-shaped nail to the inner wall of the femoral canal for effective fixation. A comprehensive analysis of the mechanical testing results of pig femur models with metaphyseal, midshaft, and supracondylar bone defects fixed using the petal-shaped intramedullary nail combined with bone cement showed that in the metaphyseal and midshaft bone defect models, the compressive strength reached 800–1000 kg, and the bending resistance reached 300–450 kg, indicating strong fixation. In the supracondylar bone defect model, the compressive strength reached 370 kg, and the bending resistance reached 180 kg, approximately half the value of the other two models, suggesting moderate fixation. Based on the failure patterns in mechanical testing, the cause is attributed to the structural characteristics of the femoral condyle and supracondylar region, where cortical bone is sparse and cancellous bone is predominant. The bonding strength of bone cement with cancellous bone is inferior to that with cortical bone, and under loading, the cancellous bone at the interface is prone to fracture and loosening, resulting in significantly lower fixation strength compared to the metaphyseal and midshaft regions.

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Torsional resistance testing showed that all three models only achieved 40%–50% of the maximum torsional resistance value of the control group, which is considered moderate. This suggests that relying solely on bone cement adhesion to the medullary canal wall cannot provide significant torsional resistance. Direct fixation of the petal-shaped intramedullary nail to the bone wall is needed to enhance torsional resistance, and this requirement is precisely met by the interlocking intramedullary nail fixation method.

In previous clinical applications, interlocking nails have been used for the treatment of femoral shaft fractures, achieving effective fixation in terms of compressive, torsional, and bending resistance. For enhancing the fixation strength of supracondylar fractures, the reverse interlocking technique can be used [23–25]. The structural feature of the interlocking intramedullary nail is that it is hollow and has locking holes at both ends, allowing the proximal and distal ends of the nail to be fixed to the femur with locking screws. This achieves central fixation, controls shortening and rotation, maintains limb length, and reduces varus or valgus deformities. However, the drawback is that the interlocking nail has relatively poor control over the stability of fracture ends. When fractures are unstable or nonunion occurs, part of the longitudinal load is transferred into shear forces between the nail and the locking screws under static fixation. Long-term loading causes fatigue and potential breakage of the screws [23,26,27].

As femoral shaft metastases are generally difficult to cure, pathological fractures caused by bone destruction are difficult to heal, and fracture instability makes the risk of screw breakage much higher than in traumatic fractures. Therefore, in clinical practice, interlocking nails for femoral shaft metastases are often combined with open reduction, lesion curettage, and bone cement filling at the fracture ends. This allows the proximal and distal fracture ends and the medullary cavity to form an integrated construct with bone cement and the intramedullary nail, eliminating micromotion caused by nonunion, significantly improving stability and load-bearing strength, reducing the risk of nail breakage, significantly relieving postoperative pain, partially or completely restoring limb function, improving quality of life, and reducing nursing difficulty for patients [16,28,29].

However, for patients who cannot tolerate major surgery and have limited life expectancy but high expectations for quality of life, percutaneous cementoplasty has been used to treat impending fractures of long bone metastases, achieving relatively satisfactory results. Yet, postoperative fracture rates remain high [30]. There have also been reports of treating femoral shaft metastases with closed interlocking nail fixation, which has the advantages of minimal trauma, fast recovery, satisfactory functional outcomes, and significant pain relief [12]. Nevertheless, in clinical applications, it has been found that combining closed reduction interlocking nails with bone cement is technically challenging. The intramedullary nail must be placed first, followed by puncture into the lesion to inject bone cement. However, due to obstruction by the nail or cortical wall, bone cement often cannot sufficiently fill the proximal and distal fracture ends and the medullary cavity. Thus, the goal of forming a unified composite of cement and intramedullary nail is difficult to achieve, requiring multiple punctures and increasing the risk of tumor seeding along puncture tracks.

This study demonstrated through mechanical testing that the method of petal-shaped intramedullary nail combined with bone cement fixation is equally feasible as the previously reported method of interlocking nail combined with bone cement for the treatment of femoral shaft metastases, with each approach having its own advantages and disadvantages. Based on the experimental results and past clinical experience, combining the structural advantages of both types of nails may solve the problem of bone cement injection into the medullary cavity and provide new insight into developing a bone cement–compatible interlocking intramedullary nail suitable for minimally invasive treatment of femoral shaft metastases.

6. Conclusion and perspective

This experiment demonstrated that the structural advantage of the petal-shaped intramedullary nail allows easy injection of bone cement into the medullary cavity and enables firm integration with the cement. Mechanical testing of pig femur models showed no separation between the nail and cement composite after fracture, indicating strong bonding.

This fixation method achieved strong fixation in metaphyseal and midshaft femoral bone defect models, but only moderate fixation in supracondylar defects, suggesting the need for structural improvement of the petal-shaped nail.

Combining the structural advantages of petal-shaped and interlocking nails may lead to the design of a novel bone cement–compatible intramedullary nail, potentially achieving true minimally invasive treatment for long bone metastases in patients with advanced cancer.

As proposed by Director Wei Guo in the Chinese Journal of Clinical Oncology, with advances in comprehensive treatment for malignant tumors and prolonged survival, the incidence of bone metastases is increasing annually. Standardized treatment for bone metastases has become an

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important and challenging task. In the field of bone metastasis treatment, there are still many methods to be developed, such as surgical intervention, drug therapy, and minimally invasive techniques. Much work remains to be done in these areas [31]. Currently, there is no universally accepted fixation method or implant that achieves truly minimally invasive treatment for long bone metastases. The next step is to integrate the structural advantages of both petal-shaped and interlocking nails to design a bone cement–compatible intramedullary implant, solve the issue of cement injection into the medullary cavity, and ultimately achieve minimally invasive treatment for long bone metastases in terminal cancer patients.

LIST OF ABBREVIATIONS

Not involved.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The project submitted by Jiamao Dong (YKD202002017) has been reviewed by the Medical Ethics Committee of Inner Mongolia Medical University. It complies with ethical principles and is approved for implementation.

HUMAN AND ANIMAL RIGHTS

Not involved.

CONSENT FOR PUBLICATION

Not involved.

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AVAILABILITY OF DATA AND MATERIALS

Not involved.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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