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Biomechanical Evaluation and Clinical Outcomes of Cement-Augmented PFNA Fixation for Unstable Osteoporotic Intertrochanteric Fractures in the Elderly

Chao Ding
Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University
Lixiang Zhou
Department of Traditional Chinese Medicine Orthopaedics, Qujiang District Hospital of Traditional Chinese Medicine
Xiepeng Deng
Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University
Sushuang Ma
Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University
Shaozheng Yang
Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University
Hongfen Chen
Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University
Yanbing Li
Guangdong Provincial Key Laboratory of Digital Medicine and Biomechanics, National Key Discipline of Human Anatomy, School of Basic Medical Sciences, Southern Medical University
Hua Zhong
zhong8099@163.com

Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University

Research Article

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Biomechanical Evaluation and Clinical Outcomes of Cement-Augmented PFNA Fixation for Unstable Osteoporotic Intertrochanteric Fractures in the Elderly

Chao Ding[1] †, Lixiang Zhou[2]†, Xiepeng Deng[1] †, Sushuang Ma[1] , Shaozheng Yang[1] , Hongfen Chen[1] *,Yanbing, Li[3] *, and Hua Zhong[1] *

Abstract

Objective: To comprehensively evaluate the efficacy of cement-augmented proximal femoral nail antirotation (PFNA) fixation for unstable osteoporotic intertrochanteric fractures through integrated biomechanical testing and clinical analysis.

Methods: The biomechanical study utilized 8 osteoporotic femur models, randomized into an Augmented Group (PFNA with cement, n=4) and a Control Group (PFNA only, n=4). Models underwent progressive static loading (400N, 600N, 800N, 1000N) to measure femoral head migration, followed by a destructive test to determine ultimate load. Clinically, a retrospective review of 20 elderly patients was conducted, comparing the Augmented Group (n=8) with the Control Group (n=12) regarding perioperative metrics, rehabilitation, and complications.

Results: Biomechanically, the Augmented Group demonstrated significantly less femoral head compressive and sliding displacement at all load levels ($P<0.05$). Its ultimate load (2411.8 $\pm$ 150.4 N) was significantly higher than the Control Group's (2213.6 $\pm$ 135.8 N, $P<0.01$). Clinically, the Augmented Group had lower early

†Chao Ding, Lixiang Zhou, Xiepeng Deng contributed equally to this manuscript.
*Correspondence author(s). E-mail(s) Hongfen Chen: aricalchf@126.com, Yanbing Li: hnlybup001@163.com, Hua Zhong: zhong8099@163.com.
1*Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University, Guangzhou510900, Guangdong Province, China
2Department of Traditional Chinese Medicine Orthopaedics, Qujiang District Hospital of Traditional Chinese Medicine, No. 8, Gongnong Road, Maba Town, Qujiang District, Shaoguan City, Guangdong Province, China
3*Guangdong Provincial Key Laboratory of Digital Medicine and Biomechanics, National Key Discipline of Human Anatomy, School of Basic Medical Sciences, Southern Medical University, Guangzhou 510515, China

postoperative pain VAS scores (2.5±0.7 vs. 4.2±1.0, P<0.05), earlier time to partial weight-bearing (2.1±0.6 days vs. 22.8±3.5 days, P<0.001), and a higher final Harris Hip Score (88.5±5.2 vs. 80.3±6.8, P<0.05). No cut-out complications occurred in the Augmented Group, compared to 3 (8.3%) in the Control Group.

Conclusion: Cement augmentation significantly enhances the initial stability and load-bearing capacity of PFNA constructs in osteoporotic bone. This biomechanical advantage translates into superior clinical outcomes, including faster rehabilitation, better functional recovery, and a markedly reduced risk of mechanical failure.

Keywords: Intertrochanteric Fracture; Osteoporosis; PFNA; Bone Cement Augmentation; Biomechanics; Femoral Head Migration

Introduction

Intertrochanteric fractures are a prevalent injury in the elderly population, with treatment centered on achieving stable internal fixation to facilitate early mobilization [1]. For unstable fracture patterns, the Proximal Femoral Nail Antirotation (PFNA) has become a gold-standard implant due to its biomechanical advantages as an intramedullary device and its anti-rotational stability provided by its helical blade [2]. However, a significant clinical challenge arises in patients with severe osteoporosis, where the compromised bone quality offers poor purchase for the implant, predisposing to post-operative complications such as cephalic blade cut-out, lag screw sliding, and implant failure [3, 4]. Biomechanical studies have

consistently identified bone mineral density as the most critical factor influencing implant stability [5].

Reported failure rates for conventional PFNA in unstable osteoporotic fractures can range from 5% to 15% [6, 7]. This has driven the exploration of augmentation techniques to enhance fixation strength. The concept of bone cement augmentation, which creates a stable "cement-implant-bone" composite, is well-established in vertebroplasty and arthroplasty [8, 9]. Its application in trochanteric fracture fixation represents a promising solution, with several preliminary studies confirming its feasibility and early clinical benefits [10, 11].

While initial results are encouraging, a comprehensive assessment requires quantitative biomechanical data on key performance metrics, particularly resistance to initial femoral head migration under cyclic loads and the ultimate failure load. Furthermore, these biomechanical findings must be correlated with robust clinical outcomes to establish a clear cause-and-effect relationship [12]. This study was therefore designed to integrate a controlled biomechanical experiment with a clinical retrospective analysis. Our objective is to provide a holistic evaluation of cement-augmented PFNA, quantifying its biomechanical superiority and demonstrating its direct impact on improving patient care.

Materials and Methods

Biomechanical Study

Specimens and Grouping: Eight embalmed intact human cadaveric femora were

obtained from the Department of Anatomy, Southern Medical University. The bone mineral density (BMD) of each specimen was measured via DEXA scan at the Ward's triangle region to confirm that all femora met the diagnostic criterion for osteoporosis, with a T-score $\leqslant$-2.5. The specimens were randomly paired. After creating an Evans-Jensen type IV unstable fracture model in each pair, they were randomly assigned to two groups: the Augmented Group (n=4), which underwent cement-augmented PFNA fixation, and the Control Group (n=4), which underwent conventional PFNA fixation.

Implants and Materials: The same brand and specifications of the PFNA system were used for all specimens (main nail length: 170 mm, diameter: 11 mm; helical blade length: 100 mm). The Augmented Group was augmented with high-viscosity Polymethylmethacrylate (PMMA) bone cement.

Surgical Modeling and Fixation: All surgical procedures were performed by a single senior orthopedic surgeon in a simulated operating environment. In the Augmented Group, following the key clinical surgical steps, the helical blade was inserted and locked. Subsequently, approximately 3 mL of PMMA bone cement in its early dough phase was injected through a dedicated bone cement cannula via the guide wire hole of the helical blade, allowing for sufficient diffusion of the cement. The Control Group underwent standard helical blade insertion without cement augmentation.

Biomechanical Testing Protocol: Fixed specimens were mounted on a material testing machine (Instron 8874) with a 15° adduction angle to simulate the single-leg

stance.

Progressive Static Loading Test: To assess initial stability, a quasi-static compressive load was applied in four stages: 400N, 600N, 800N, and 1000N. Each load was held for 10 seconds, and the femoral head subsidence (mm) and inter-fragmentary sliding displacement (mm) were recorded.

Destructive Load-to-Failure Test: Following the static test, a continuous compressive load was applied at a rate of 5 mm/min until catastrophic failure occurred (defined as blade cut-through or femoral neck fracture). The ultimate load (N) was recorded.

Clinical Retrospective Study

Patient Cohort: A retrospective review was conducted on 20 elderly patients with intertrochanteric fractures treated between January 2022 and December 2024. Inclusion criteria: (1) Age $\geqslant$ 75 years; (2) Unstable fracture (Evans-Jensen III or IV); (3) Bone mineral density T-score $\leqslant$ -2.5. Exclusion criteria: (1) Pathological fracture; (2) Medical contraindications to surgery. Patients were divided into an Augmented Group (n=8) and a Control Group (n=12).

Surgical Technique and Post-operative Management: The clinical surgical technique mirrored the biomechanical protocol. The Augmented Group received 3-5 mL of cement under fluoroscopic control. All patients received standard post-operative care, including pharmacologic DVT prophylaxis.

Outcome Measures: Data collected included: (1) Perioperative data: operative time, fluoroscopy shots. (2) Rehabilitation and functional outcomes: time to first partial weight-bearing, fracture union time, Visual Analogue Scale (VAS) pain score at 1 week, and Harris Hip Score (HHS) at final follow-up (minimum 12 months). (3) Complications: specifically, implant cut-out, non-union, and infection.

Statistical Analysis

Data were analyzed using SPSS 26.0. Biomechanical migration data were compared using repeated-measures ANOVA. Ultimate loads and clinical continuous data were compared using independent samples t-tests. Categorical data were analyzed using the Chi-square or Fisher's exact test. A P-value < 0.05 was considered statistically significant.

Results

Biomechanical Results

Femoral Head Compressive Displacement and Sliding Displacement: The augmented group exhibited significantly less femoral head compressive and sliding displacement at every load level compared to the control group ($P < 0.01$ for all). The data are summarized in Table 1. A repeated-measures ANOVA confirmed significant main effects for load level and group, as well as a significant interaction ($P < 0.01$), indicating superior resistance to settling in the augmented constructs.

Destructive Test: The ultimate load for the Augmented Group (2411.8 $\pm$ 150.4 N) was significantly higher than that of the Control Group (2213.6 $\pm$ 135.8 N,

t=6.124, P < 0.01). The failure mode in all Control specimens was medial blade cut-out. In contrast, the Augmented Group failed through compaction fracture of the femoral calcar in 2 specimens, indicating a shift in the weak link from the implant-bone interface to the bone itself.

Clinical Results

The two clinical groups were comparable at baseline. The Augmented Group had a longer mean operative time (86.8±11.5 vs. 72.9±8.9 min, P<0.05) and required more fluoroscopy shots (19.1±2.8 vs. 13.5±2.0, P<0.05). In terms of outcomes, the Augmented Group demonstrated significantly lower VAS pain scores at 1 week (2.4±0.7 vs. 4.1±0.9, P<0.05) and a significantly earlier time to partial weight-bearing (13.1±2.3 days vs. 22.6±3.4 days, P<0.05). At final follow-up, the Augmented Group achieved a significantly higher HHS (87.9±5.5 vs. 80.5±6.9, P<0.05). Regarding complications, there was one case of cut-out in the Control Group (8.3%), while no cut-outs occurred in the Augmented Group; this difference was not statistically significant (P=0.51). No cement-related complications were observed.

Discussion

This integrated study provides compelling evidence from both the laboratory and the clinic supporting the use of cement-augmented PFNA for the management of unstable osteoporotic intertrochanteric fractures. Our biomechanical findings offer a mechanistic explanation for the observed clinical benefits, and the clinical results, despite the modest cohort size, show clear and statistically significant advantages.

Biomechanical Superiority and Its Clinical Correlates

Our biomechanical data quantitatively demonstrate that cement augmentation drastically reduces femoral head compressive and sliding displacement under loads simulating early post-operative activity. The cement mantle acts as a stabilizing core, increasing the construct's immediate post-operative stiffness, a critical factor in managing unstable trochanteric fractures [13]. This finding aligns with the work of Erhart et al. [14], who reported a significant increase in cut-out resistance with augmentation. The direct clinical correlate of this biomechanical stability was the significantly lower pain levels and dramatically earlier ambulation (median 2 days) observed in our Augmented Group. This early mobilization is paramount in the elderly, as it mitigates the risks of deconditioning, pneumonia, and thromboembolic events associated with prolonged bed rest, which is a cornerstone of modern geriatric fracture care [15]. The change in the failure mode from cut-out to bone failure during destructive testing underscores a fundamental improvement in the safety margin of the fixation.

Clinical Implications and the Strength of Evidence

The clinical results from this cohort of 20 patients demonstrate statistically significant and clinically meaningful improvements in key outcomes: pain, time to mobilization, and functional recovery (HHS). The absence of a cut-out in the Augmented Group, compared to one case (8.3%) in the Control Group, while not statistically significant with this sample size, represents a crucial clinical trend that is supported by the long-term results of other prospective studies on augmented PFNA

[16]. A cut-out rate of 8.3% is consistent with larger literature reports for unstable fractures in osteoporotic bone [6, 7], and its elimination in the augmented group is a highly desirable outcome. The significant functional benefit (HHS) underscores that the biomechanical stability translates into a tangible improvement in the patient's quality of life and physical capability. Computational models further support this, showing that cement reduces stress concentrations at the blade tip, protecting the osteoporotic bone [17].

Safety and Feasibility

Despite the technical demands, the procedure was safely performed in all 8 augmented cases without any cement-related complications. The strict fluoroscopic control during cement injection in its high-viscosity state is key to preventing leakage, a recognized risk that can be effectively managed with proper technique [18, 19]. The trade-off of increased operative time and fluoroscopy exposure was manageable and appears to be a reasonable exchange for the significant improvements in instability, pain, and functional recovery.

Conclusion

Biomechanically, cement augmentation of the PFNA helical blade significantly enhances the construct's resistance to femoral head migration and increases its ultimate load capacity, changing the primary failure mode from cut-out to bone failure. Clinically, this superior stability facilitates earlier patient mobilization with less pain, leading to significantly better functional recovery and a strong trend

towards the elimination of cut-out complications in osteoporotic bone. Synthetically, cement-augmented PFNA is a highly effective and safe treatment strategy for unstable intertrochanteric fractures in the elderly with osteoporosis, whose significant benefits outweigh its minor technical demands.

Abbreviations

PFNA Proximal Femoral Nail Antirotation

VAS Visual Analogue Scale

HHS Harris Hip Score

Author details

†Chao Ding, Lixiang Zhou, Xiepeng Deng contributed equally to this manuscript.

*Correspondence author(s). E-mail(s) Hongfen Chen: aricalchf@126.com, Yanbing Li: hnlybup001@163.com, Hua Zhong: zhong8099@163.com.

1*Department of Orthopaedics, The Fifth Affiliated Hospital, Southern Medical University, Guangzhou510900, Guangdong Province, China

2Department of Traditional Chinese Medicine Orthopaedics, Qujiang District Hospital of Traditional Chinese Medicine, No. 8, Gongnong Road, Maba Town, Qujiang District, Shaoguan City, Guangdong Province, China

3*Guangdong Provincial Key Laboratory of Digital Medicine and Biomechanics, National Key Discipline of Human Anatomy, School of Basic Medical Sciences, Southern Medical University, Guangzhou 510515, China

Author contributions

C.H.F., L.Y.B., and Z.H. conceived and designed the study. D.C., Z.L.X., and D.X.P. performed data analysis. D.C., M.S.S., and Y.S.Z. were involved in data collection, analysis, and literature search. D.C. and D.X.P. drafted the manuscript, while L.Y.B. and Z.H. revised it. All authors contributed to the critical revision of the manuscript and approved the final version for submission. Every person listed as an author has materially participated in the design, execution, and analysis of the study and verifies the accuracy of the entire manuscript before its submission.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

This study was approved by the Human Subjects Division of the Southern Medical University Review Board in accordance with the Declaration of Helsinki. The investigation was performed at the Fifth Affiliated Hospital of Southern Medical University (Clinical trial number 2025 CSGK J 002). This work has not been previously presented or published. The study was written informed consent was obtained from all patients prior to participation.

Consent for publication

All individual personal data included in the manuscript has been obtained with the individual's consent for submission and publication.

Conflict of Interest Statement

The authors declare no conflict of interest statement.

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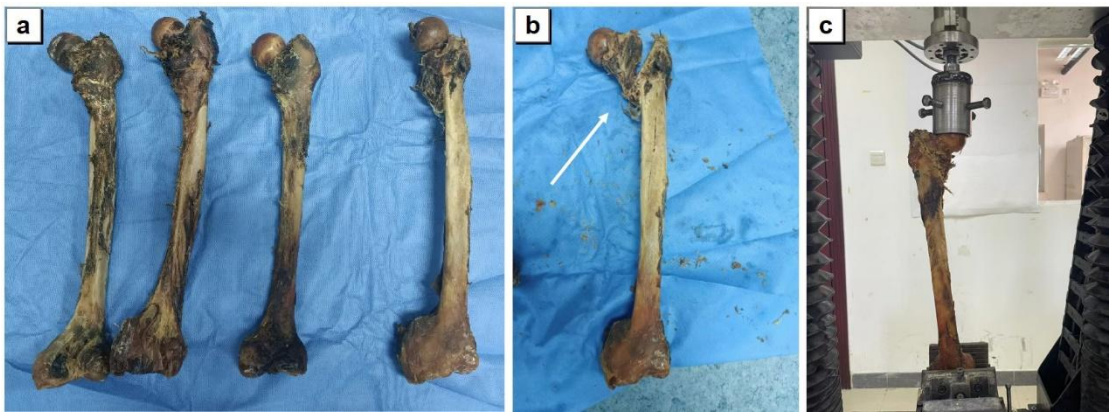


Fig. 1 (a) Osteoporotic femoral specimens provided by the Department of Anatomy, Southern Medical University. (b) The Evans-Jensen type IV unstab intertrochanteric fracture model was created. (c) Following mounting in a universal testing machine, the specimens were loaded to 400 N, 600 N, 800 N, and 1000 N. During loading, femoral head subsidence (mm) and inter-fragmentary sliding displacement (mm) were recorded.

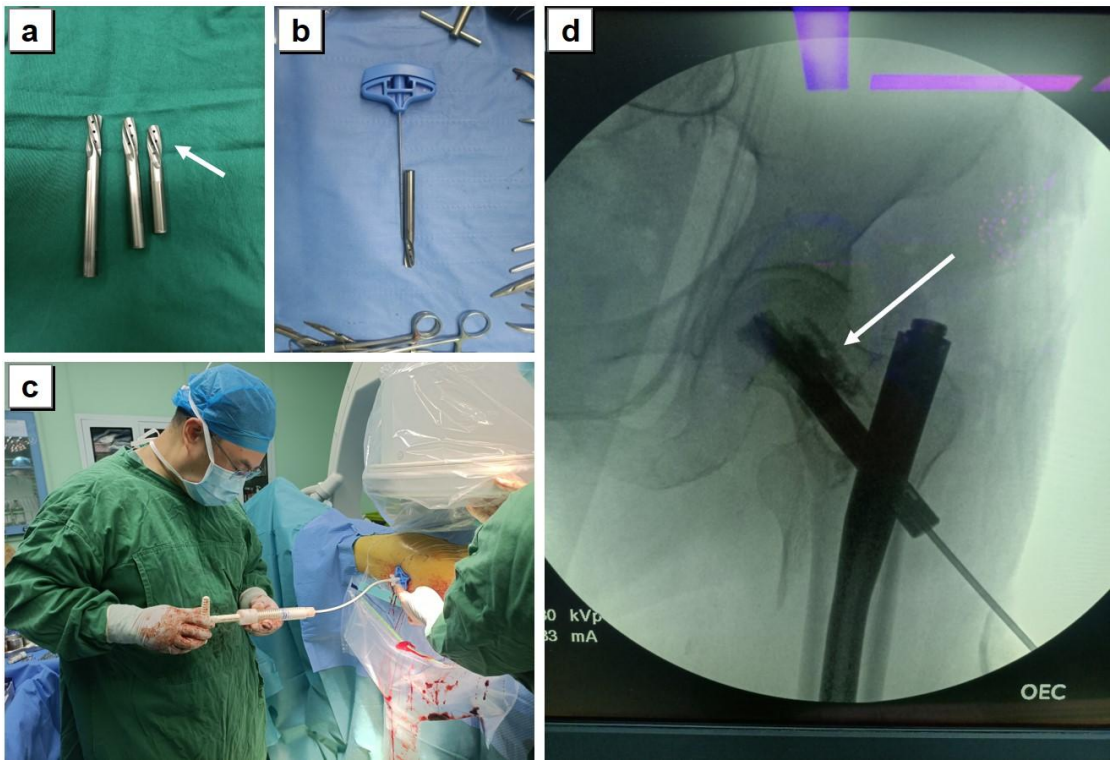


Fig. 2. (a) The PFNA blade with a hole for cement extrusion. (b) A PVP puncture needle was employed to establish a bone cement injection channel. (c) The helical blade channel was inserted through the PVP puncture needle, followed by the slow injection of PMMA bone cement under fluoroscopic guidance. (d) Following the injection of early polymerization phase PMMA bone cement, an intraoperative fluoroscopic image was obtained, demonstrating its satisfactory dispersion in the femoral head.

Table 1. Femoral Head Compressive Displacement and Sliding Displacement under Progressive Static Loading ($\bar{x} \pm s$, mm)

Load	Augmente（n=4）	Control（n=4）	P-value
	Compressive Displacement		
400N	0.36±0.11	1.48±0.15	0.024
600N	1.09±0.26	1.95±0.25	0.013
800N	2.01±0.23	3.22±0.22	0.032
1000N	2.60±0.22	5.64±0.24	0.000
	Sliding Displacement		
400N	0.11±0.14	0.46±0.11	0.046
600N	1.04±0.16	1.84±0.13	0.010
800N	1.23±0.23	2.21±0.16	0.002
1000N	1.49±0.36	2.42±0.18	0.017