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Research Article

Biomechanical comparison of an intramedullary nail combined with a reconstruction plate combination versus a single intramedullary nail in unstable intertrochanteric fractures with lateral femoral wall fracture: A finite element analysis

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ABSTRACT

Objective: This study aimed to compare the biomechanical performance of an intramedullary nail combined with a reconstruction plate and a single intramedullary nail in the treatment of unstable intertrochanteric femoral fractures with a fracture of the lateral femoral wall (LFW).

Methods: A three-dimensional finite element (FE) femur model was established from computed tomography images of a healthy male volunteer. A major reverse obliquity fracture line, associated with a lesser trochanteric fragment defect and a free bone fragment of the LFW, was developed to create an AO/OTA type 31-A3.3 unstable intertrochanteric fracture mode. Two fixation styles were simulated: a long InterTAN nail (ITN) with or without a reconstruction plate (RP). A vertical load of 2100 N was applied to the femoral head to simulate normal walking. The construct stiffness, von Mises stress, and model displacement were assessed.

Results: The ITN with RP fixation (ITN/RP) provided higher axial stiffness (804 N/mm) than the ITN construct (621 N/mm). The construct stiffness of ITN/RP fixation was 29% higher than that of ITN fixation. The peak von Mises stress of the implants in the ITN/RP and ITN models was 994.46 MPa and 1235.24 MPa, respectively. The peak stress of the implants in the ITN/RP model decreased by 24% compared to that of the ITN model. The peak von Mises stress of the femur in the ITN/RP model was 269.06 MPa, which was lower than that of the ITN model (331.37 MPa). The peak stress of the femur in the ITN/RP model was 23% lower than that of the ITN model. The maximum displacements of the ITN/RP and ITN models were 12.12 mm and 13.53 mm, respectively. The maximum displacement of the ITN/RP model decreased by 12% compared with that of the ITN model.

Conclusion: The study suggested that an additional plate fixation could increase the construct stiffness, reduce the stresses in the implant and femur, and decrease displacement after intramedullary nailing. Therefore, the intramedullary nail and reconstruction plate combination may provide biomechanical advantages over the single intramedullary nail in unstable intertrochanteric fractures with a fractured LFW.

Introduction

Despite great efforts made by orthopedic trauma surgeons, unstable intertrochanteric fractures are still associated with high rates of complications and mortality,[1] which have become an important public health concern and will be a heavy economic burden for society.[2] Therefore, it is challenging to choose an appropriate fixation method for unstable femoral fractures.

In recent years, most researchers have realized that an intact lateral femoral wall (LFW) plays an important role in the surgical stabilization of unstable intertrochanteric fractures.[3-5] The LFW, which was initially described by Gotfried,[3] provides a lateral buttress for sliding of the head–neck fragment, and its integrity preoperatively has been proposed to be the main factor in deciding internal fixation implantation for fracture stabilization. Additionally, postoperative fracture of the LFW was proven to be a major predictor for the reoperation of an intertrochanteric fracture fixed with a compression hip screw.[4] Furthermore, LFW thickness was found to be an important predictor of secondary LFW fractures treated with dynamic hip screws (DHS).[5] Thus, an angular stable trochanter-stabilizing plate (TSP) was introduced to provide an additional buttress force to strengthen DHS fixation, and DHS combined with TSP could obtain satisfactory surgical outcomes in patients with incompetent LFW.[6] However, the addition of TSP could result in further damage to the soft tissue, resulting in more residual pain and implant irritation.[6]

Compared with DHS fixation, intramedullary devices are widely used for minimal surgical trauma, better biomechanical performance, and satisfactory functional outcomes.[7] Substantial evidence has proven that the nail itself could play the role of a lateral buttress and prevent excessive sliding of the head-neck fragment.[8] However, intramedullary fixation encounters great

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difficulties in reducing or fixing the LFW when it is broken, which might increase the instability of unstable intertrochanteric fractures. Accordingly, implant failure remains one of the most serious complications after surgery for unstable intertrochanteric fractures.[9] To achieve satisfactory reduction of the fractured LFW, a reconstruction plate (RP) was used and demonstrated to be effective in clinical research.[10]

Proximal femoral nail antirotation (PFNA) with a helical blade and InterTAN nail (ITN) (Smith & Nephew, Memphis, Tennessee) with 2 integrated cephalocervical screws are 2 widely used intramedullary devices for intertrochanteric fractures.[11,12] A meta-analysis of randomized controlled trials and observational studies showed that ITN offers a lower risk of revision, fewer long-term implant failures, and less postoperative pain compared to PFNA.[11] However, whether the long ITN is stable enough for unstable intertrochanteric fractures with a fractured LFW remains controversial.

The purpose of our study was to verify whether a long ITN combined with a RP is superior to a single ITN in the treatment of unstable intertrochanteric femoral fractures involving a fracture of the LFW using finite element (FE) analysis method. Construct stiffness, von Mises stress distributions, and model displacement would be assessed. Our hypothesis was that adding a RP to a long nail would provide better stability, reduce implant stress, and therefore implant failure could be reduced by this method.

Material and methods

Finite element modeling

One healthy male volunteer (age, 60 years; weight, 70 kg; height, 172 cm) was selected for this study. Institutional review board approval and ethics approval were obtained before initiation of the study from the Ethics Committee of Shanghai Pudong New Area People's Hospital (Approval No: prylz2020-054; Date: May 13, 2020). Written informed consent was obtained from the patient who participated in this study. Standard radiographs of the femur were obtained to exclude femoral fractures or other abnormalities. The right lower extremity was scanned using computed tomography (CT) (Philips Brilliance 64CT, Philips Healthcare, Netherlands) for reconstruction of femur geometry. DICOM data were imported into Mimics 21.0 software (Materialize, Leuven, Belgium) to reconstruct the geometry of the femur from the CT images.

To simulate unstable intertrochanteric fractures with a fracture of the LFW, a fracture type of AO/OTA (the AO Foundation/Orthopaedic Trauma Association) 31-A3.3 was simulated according to the model described by Meinberg et al,[13] with a major reverse obliquity fracture line, associated with a lesser trochanteric fragment defect and a free bone fragment of the LFW. Two types of implants were modeled and simulated: long ITN and RP. Three-dimensional models

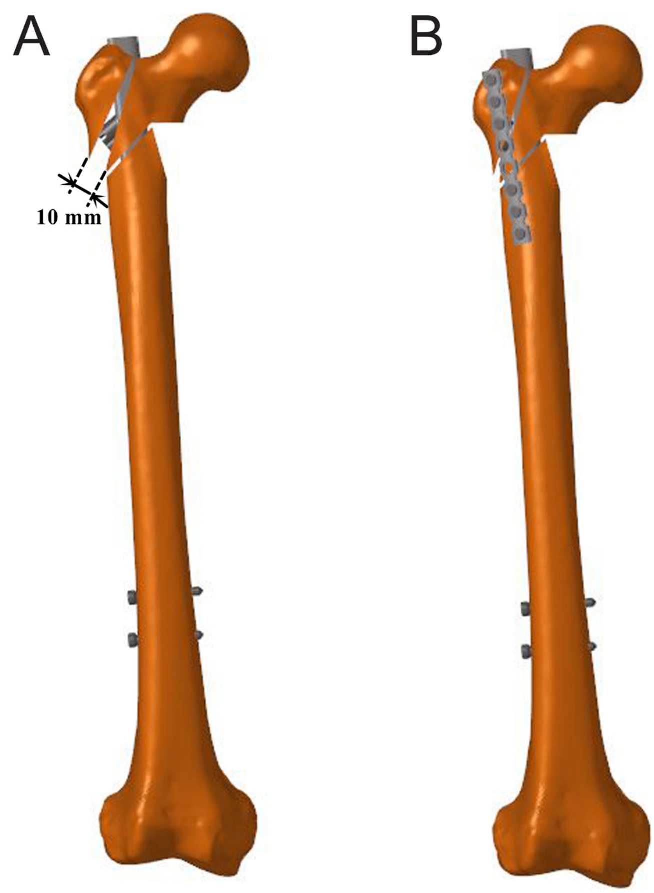

Figure 1. Finite element model of intertrochanteric fracture with a free lateral wall fragment fixed by 2 types of implants: (A) ITN model. (B) ITN/RP model. ITN, InterTAN nail; RP, reconstruction plate.

of intramedullary nails (length 340 mm, diameter 10 mm, 4° proximal lateralization angle, center-column-diaphyseal angle 130°, integrated cephalocervical screws 90 mm and 85 mm, Titanium, Smith & Nephew) and plate (3.5-mm RP, length 94 mm, 8 holes, Stainless, Smith & Nephew) were drawn according to the manufacturer's catalog using the computer-aided design software SolidWorks 2017 (Dassault Systemes, USA). The screws were modeled as a 3.5-mm diameter.

The geometric model of the implants was assembled with a 31-A3.3 fracture model according to the product guidelines and our clinical experience. The ITN was positioned as recommended by the manufacturer's manual, as shown in Figure 1A, and the tip-apex distance was controlled within 20 mm, whereas the displaced LFW fragment did not have a good quality of reduction because some fracture gap (the distance from the apex of the LFW fragment to the lateral border of the femur) inevitably remains after operation. For ITN with RP fixation (ITN/RP), the plate was positioned on the anterolateral surface of the proximal femur, and the displaced LFW fragment achieved good quality reduction, as shown in Figure 1B.

The models of the fracture and implants were processed using the Geomagic Studio 2017 software (3D System, USA) and then imported

HIGHLIGHTS

- Lateral femoral wall integrity plays a pivotal role in surgical stabilization of intertrochanteric fractures. This biomechanical study aimed to compare an intramedullary nail combined with a reconstruction plate and a single intramedullary nail in the treatment of unstable intertrochanteric femoral fractures with a fracture of the lateral femoral wall.
- Results showed higher axial stiffness, less peak von Mises stress of the implants and smaller maximum displacement values for the intramedullary nail combined with a reconstruction plate, compared to a single intramedullary nail.
- The results indicate that intramedullary nail with a reconstruction plate could provide a more stable and biomechanically superior fixation for unstable intertrochanteric femoral fractures with a lateral femoral wall defect.

Table 1. Number of nodes and elements of femur and implants

	Cortical bone	Cancellous bone	ITN	RP
Node	462522	151160	110406	71932
element	2377573	774231	501877	316975

ITN, InterTAN nail; RP, reconstruction plate.

Table 2. Material properties of cortical and cancellous bone, titanium alloy, and stainless steel

Material	Young's modulus (Mpa)	Poisson's ratio
Cortical bone	17 000	0.33
Cancellous bone	1000	0.3
InterTAN (Ti-6Al-4 V)	113 800	0.34
Stainless steel	195 000	0.3

Table 3. Parameters results

Parameters	ITN model	ITN/RP model
The peak von Mises stress of the implant (Mpa)	1235.24	994.46
The peak von Mises stress of the femur (Mpa)	331.37	269.06
The maximum displacement of the entire assembly (mm)	13.53	12.12

ITN, InterTAN nail; RP, reconstruction plate.

into the FE software ANSYS Workbench 17 (ANSYS, Inc., USA) to draw the mesh. The models were meshed with 3-dimensional 10-node tetrahedron elements. The number of nodes and elements of the femur and implants are listed in Table 1. A mesh convergence test was conducted to determine the optimal element size. After measurement, the mesh sizes for the femur and the implants were 1.2 mm, and 0.6 mm, respectively.

Material properties

All the materials involved in the models were assumed to be homogeneous, isotropic, and linearly elastic. The ITN was made of a titanium alloy, and the RP was made of stainless steel. In the current study, the material properties of the femur and implants were adopted from previously published reports[14,15] and are listed in Table 2.

Boundary and loading conditions

With respect to the boundary conditions, all degrees of freedom at the distal end of the femur are fully constrained.[16] The coefficient of friction of the contact between the fracture surfaces was set to 0.46.[17] A friction coefficient of 0.3 was used for the bone–implant interactions,[18] except that the RP construct was fully tied to the bone. The coefficient of friction was 0.2 for the implant-implant interactions,[18] except for the 2 integrated cephalocervical screws that were fully bonded and the screws were fully tied to the plate. An angle of 15° between the axis of the femoral shaft and the body axis mimics the physiological loading of the proximal femur in the one-legged stance phase of gait.[19] Our study simulated the forces acting on the hip joint during walking.[20] To simplify the calculations, the vertical load on the femoral head was set to 2100 N (3 times the body weight).

Evaluation criteria

The FE analysis was performed using ANSYS Workbench 17 software. In this study, biomechanical stability was represented by construct stiffness and model displacement. Construct stiffness was defined as the ratio of 2100 N vertical loading to the maximum vertical displacement of the femur in the load direction. In addition, the von Mises stress distribution and peak values of the implants and femurs were assessed. A larger construct stiffness and smaller maximum model displacement represent better biomechanical stability. Lower peak stress of the implants was associated with a lower risk of implant failure. A lower peak stress of the femur represents a lower risk of femur fractures.

Results

Model validation

To validate our FE models, a model of an intact femur was simulated, and then the axial stiffness of the intact femur was compared to a cadaveric study.[21] In their study, 1500 N vertical loading was applied to the femoral head to mimic physiological loading. The results of the axial stiffness in our FE model were in good agreement with existing experimental findings. The axial stiffness of our FE model was 909 N/mm, which is comparable to that of a cadaveric model (757 ± 264

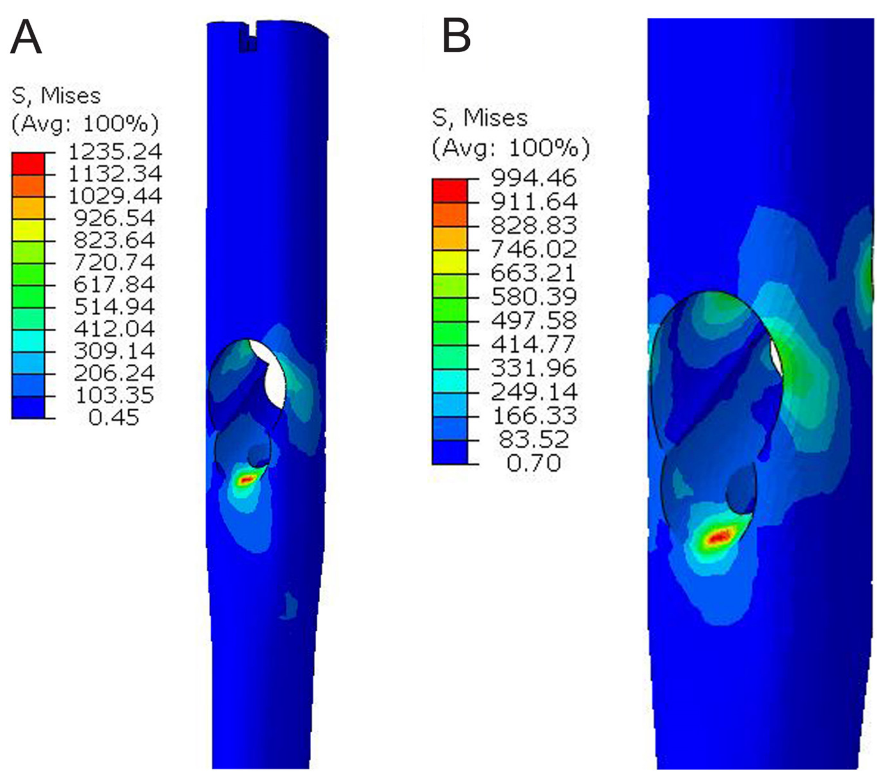

Figure 2. Von Mises stress distribution (MPa) of the 2 implants: (A) ITN model. (B) ITN/RP model. ITN, InterTAN nail; RP, reconstruction plate.

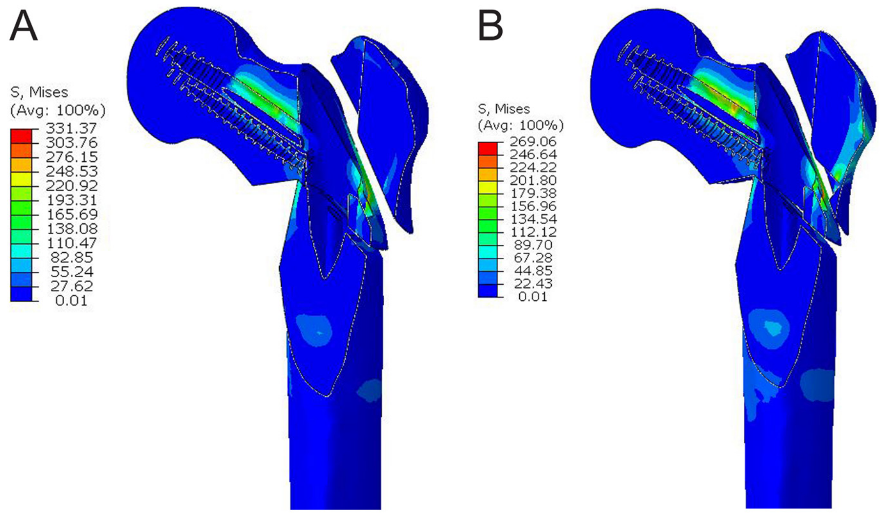

Figure 3. Von Mises stress distribution (MPa) of the femur: (A) ITN model. (B) ITN/RP model. ITN, InterTAN nail; RP, reconstruction plate.

N/mm).[21] These small disparities may be due to variations in bone quality and individual differences.

Construct stiffness

The ITN/RP fixation provided higher axial stiffness (804 N/mm) than the ITN construct (621 N/mm). The construct stiffness of ITN/RP fixation was 29% higher than that of ITN fixation.

Stress distribution

The von Mises stress distributions of the 2 implants are shown in Table 3, Figure 2A and B. In both ITN and ITN/RP fixations, the peak von Mises stress was concentrated at the junction of the main nail and integrated cephalocervical screws. The results demonstrated that the ITN/RP model had a smaller peak von Mises stress than that of the ITN model. The values of the peak von Mises stress in the ITN/RP and ITN model were 994.46 MPa and 1235.24 MPa, respectively. The peak stress of the ITN/RP model decreased by 24% compared to that of the ITN model.

The von Mises stress distribution of the femur is presented in Table 3, Figure 3A and B. In the femur, the von Mises stress peak was mainly concentrated in the lateral part of the upper cephalocervical screw hole. The peak von Mises stress value of the ITN/RP model was 269.06 MPa, which was lower than that of the ITN model (331.37 MPa). The peak stress of the ITN/RP model was 23% lower than that of the ITN model.

Model displacement

Table 3 shows the model displacement distributions for different constructs. The maximum displacement of the entire bone–implant assembly was located at the top of the femoral head for both models. The ITN/RP model appeared to have a smaller maximum displacement than the ITN model. The maximum displacements of the ITN/RP and ITN model were 12.12 mm and 13.53 mm, respectively. The maximum displacement of the ITN/RP model decreased by 12% compared with that of the ITN model.

Discussion

In recent years, FE analysis has been commonly used to evaluate the biomechanical performance of implants because it improves the treatment results of unstable intertrochanteric femoral fractures.[18] The InterTAN nail, which includes 2 integrated cephalocervical lag screws, has been proven to have biomechanical and clinical advantages over traditional intramedullary devices.[11,12] We used an RP combined with a long ITN to treat unstable intertrochanteric fractures with fractures of the LFW to obtain better LFW stability. This study aimed to determine whether an additional plate enhances the stability of the construct treated with a long ITN. In the current study, the ITN model was constructed according to our clinical experience, and the displaced LFW fragment did not have good reduction quality since single intramedullary nailing would encounter great difficulties in reducing the displaced LFW. To obtain a good reduction quality, an additional plate was used to reconstruct the integrity of the LFW in the ITN/RP model after intramedullary nail fixation.

Currently, the importance of good quality reduction of intertrochanteric fractures has attracted the attention of most trauma and biomechanical experts.[10,23,24] In a retrospective study of intertrochanteric fractures under PFNA fixation, Zhang et al[25] found that good quality reduction could reduce the risk of mechanical failure. In addition, Fan et al[23] confirmed that in intertrochanteric fractures with LFW fracture using intramedullary nail fixation, poor reduction quality was a reliable predictor of implant failure. In the current study, the ITN/RP model achieved good quality reduction with an additional plate, and the results showed that the peak stresses of the implant and femur in the ITN/RP model were lower than those in the ITN model. Furthermore, the maximum displacement in the ITN/RP model was smaller than that in the ITN model.

The 3-point fixation theory, described by Abram et al,[26] includes stability at the tip-apex distance point, LFW point, and great trochanter point. The bone–implant assembly would be stable if all 3 fixation points were positioned adequately following intramedullary nailing, and the failure rate would be less than 1%.[26] However, the LFW point loses stability when the LFW is broken. The broken LFW makes the reduction of intertrochanteric fractures extremely difficult, and the screw or blade inserted through the LFW would not provide stable fixation. Eventually, instability of the bone–implant assembly occurs, resulting in a high incidence of implant failure. Reconstruction of the LFW with a plate is an effective reduction and fixation method for the stabilization of unstable intertrochanteric fractures.

There is agreement that the combined use of a plate together with a sliding hip screw or intramedullary nail can provide better fixation stability in the treatment of unstable intertrochanteric fractures with LFW fractures. Su et al[27] biomechanically compared a lateral support plate in combination with a sliding hip screw versus a sliding hip screw alone in a cadaveric study and found that the mean lateral head displacement, mean inferior head displacement, and mean lag screw sliding distance for femurs instrumented using the lateral support plate were significantly less than the femurs fixed with the sliding hip screw alone. With an additional lateral support plate, the percentage decreases of mean lateral head displacement, mean inferior head displacement, and mean lag screw sliding distance were 34%, 38%, and 58%, respectively. Our findings are compatible with the biomechanical study by Mu et al,[28] who proved that an additional plate significantly decreased the maximum stress and maximum displacement of the intramedullary nail when the lateral and medial defects of the intertrochanteric fracture model were fixed with PFNA. The maximum stress and maximum displacement were 653 MPa and 3.84 mm for PFNA alone, whereas the values for PFNA in conjunction with a steel plate decreased to 608 MPa and 3.72 mm, respectively. A decrease in the peak stress of the implant could reduce the risk of fixation failure after definitive treatment. The additional plate seems to function as a load-sharing instrument, and the load share is transferred from the intramedullary nail to the femur. In our study, the maximum stress on the intramedullary nail was reduced by 24% using an additional plate. In another biomechanical study on synthetic femurs, AO/OTA 31-A3.3 intertrochanteric fractures were simulated and treated with a long gamma nail combined with an auxiliary locking compression plate or a long gamma nail alone, and the results suggested that an additional plate increased the axial stiffness of the bone–implant assembly and decreased the strains on the nail.[29] The additional plate also reduced the interfragmentary shear movement and rotation. In detail, when the locking compression plate was applied, the axial stiffness of the osteosynthesis increased by 23%, the magnitude of the strains on the long gamma nail decreased by at least 20%, the interfragmentary shear movement was 42% smaller, and the interfragmentary rotation was 48% smaller than that of the long gamma nail alone.[29] It is known that a reduction in interfragmentary shear micromotion is associated with faster fracture healing.[30] Therefore, additional plate fixation has been applied to reduce harmful shear micromotion in clinical studies.[10,29]

Recent studies have found that adding an additional plate to a sliding hip screw or intramedullary nail might achieve faster fracture healing in unstable intertrochanteric fractures with a fracture of the LFW. In a retrospective study, Madsen et al[31] found that in unstable proximal femoral fractures, 18% of the patients in the Gamma nail group, 34% in the compression hip screw group, and only 9% in the DHS with TSP group suffered from fixation failures, which led the authors to conclude that the use of a lateral support plate could help reduce the problem of femoral shaft medialization coupled with the compression hip screw systems and femoral shaft fractures associated with the Gamma nail. Similar retrospective data by Eberle et al[29] also observed that in intertrochanteric to subtrochanteric nonunions, fracture healing was achieved in 11 of 13 patients with long gamma nails and an additional locking compression plate. Therefore, the use of an additional plate to stabilize the fracture is considered helpful in achieving a more rapid union.

However, intramedullary nail and RP combination had a longer operation time and more intraoperative blood loss when compared with a single intramedullary nail (91.0 vs. 63.1 minutes, $P < .01$; 226.5 vs. 154.3 mL, $P < .01$, respectively).[10] Owing to the advantages of minimal invasion and better stability, Wang et al[10] observed that the fracture healing time was shorter and the fixation failure rate was lower in patients following RP and intramedullary nail fixation than in patients treated with a single intramedullary nail (11.8 vs. 14.2 weeks, $P = .03$; 6.3% vs. 31.6%, $P = .06$, respectively). Moreover, the postoperative functional scores were significantly higher in patients with a RP than in those without. Therefore, intramedullary nail and RP combination might be superior to a single intramedullary nail in terms of fracture healing time, complication fixation failure rate, and postoperative functional recovery. One must keep in mind that an additional plate might require more operation time and more intraoperative blood loss, and thus the use of an additional plate should not be recommended in some elderly patients who require urgent fixation with significant morbidity.

However, the current study had some limitations. First, the material properties of the femur and implants were assumed to be homogeneous, isotropic, and linear elastic, which could not fully reflect real conditions. Second, only static loads were applied to the femur for the FE analysis. In reality, the femur is exposed to complex forces and moments during normal activities. Finally, the forces and contributions of soft tissues and other adjacent structures are ignored in the models to reduce the complexity of the analysis. Despite this, the FE model used in this study was in agreement with those used in previous in vitro studies.

In conclusion, the present study demonstrated that the use of additional plate fixation could increase the construct stiffness, reduce the stresses in the implant and femur, and decrease the displacement after intramedullary nailing. Therefore, the intramedullary nail and RP combination may provide biomechanical advantages over a single intramedullary nail in unstable intertrochanteric fractures with a fractured LFW.

Ethics Committee Approval: This study was approved by the Ethics Committee of Shanghai Pudong New Area People's Hospital (Approval No: prylz2020-054; Date: May 13, 2020).

Informed Consent: Informed consent was obtained from the patient who agreed to take part in the study.

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Declaration of Interests: The authors have no conflicts of interest to declare.

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