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Research Article

Biomechanical Comparison of Different PFN Models on Intertrochanteric Femur Fracture Fixation

Özgür Verim[1]* and Mehmet Nuri Konya[2]

[1]Department of Mechanical Engineering, Faculty of Technology, Afyon Kocatepe University, Afyonkarahisar, Turkey

[2]Department of Orthopeadics and Traumatology, Afyonkarakisar Health Sciences University, Afyonkarahisar, Turkey

***Corresponding Author:** Özgür Verim, Assistant Professor, Department of Mechanical Engineering, Faculty of Technology, Afyon Kocatepe University, Afyonkarahisar, Turkey.

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Abstract

The best biomechanical placement of new proximal femoral nails for the stabilisation of intertrochanteric fractures on the proximal femur is not clearly specified. The aim of this study is to examine the biomechanical differences of three different proximal femoral nails used on intertrochanteric fractures. Radiographic image data obtained from computed tomography were used to create the three-dimensional model. The implants were modelled with the Geomagic Design X program, a reverse engineering software, and assembled with the femur bone. The most active muscles on the femur were taken into account during the analysis, which assumed application of a load equivalent to the one-leg stance phase during gait. According to the results of the finite element analysis performed with the Ansys program, the equivalent von Mises stress differences on the three different proximal femoral nails are clearly shown. As a result of the comparison, it was seen that the Group-DS and Group-HSS implants were close to each other and the Group-SS implant produced a more stable result compared to the others.

Keywords: *Intertrochanteric Fracture; Modular Prosthesis Nail Combination; Classic Proximal Femoral Nail; Talon Distal Fix Nail; Biomechanical Comparison*

Abbreviations

FEA: Finite Element Analysis; ITF: Intertrochanteric Femoral Fracture; PFN: Proximal Femoral Nail; TAD: Tip Apex Distance; HU: Hounsfield Unit

Introduction

FEA is a numerical operative model first described for use in this field in 1972 by Brekelmans and Rybicki [1] and developed rapidly parallel to the developing computer technology. By using the FEA method, serial data can be tested multiple times without ethical disturbance [2].

Treatments of ITF are varied. Proximal femoral nails, plates, screws and DHS systems can be used for fixation [3], the main aim of which is to provide rigidity and stability of the fracture fragments. PFN allow weight-bearing on the affected limb and early mobilisation, while supporting angular and rotational stability [4]. There are several PFN designs including single and double lag screws, integrated and/or lockable lag screws, and helical blade [5] and in our literature review, some clinical comparative studies have been reported [6-8]. The main aim of this fixation is to provide rigidity and stability of fracture fragments in this study and we compare three different PFN models. These groups are reported below:

- Group-SS = Modular prosthesis nail combination with single screw (SS) (Figure 1b)
- Group-DS = Classic proximal femoral nail with double screw (DS) (Figure 1a)
- Group-HSS = Talon distal fix nail hook single screw (HSS) (Figure 1c).

Intramedullary fixation is the primary surgical treatment for unstable ITF. Group-DS, Group-HSS and Group-SS are newly designed implants and their specifications are different. The SS is a new design implant whose femoral stem is modular and can be used as a hip prosthesis [3-5] with a wide surface that maintains angular and rotational stability. The talon lag screw (Group-HSS) controls rotation by way of its deployable Talons™, which engage the cortex and span more than one inch tip-to-tip at full deployment.

Group-DS has two femoral lag screws which control anti-rotation. It has two cephalocervical screws in an integrated mechanism to support compressive and rotational loading from the femoral head. FE analysis showed that the devices had a similar biomechanical effect on the fracture line. Mainly due to structural differences between the single blade, talon blade and the two screws, the Group-DS, consisting of two screws and an intramedullary nail, could share the external loads more effectively.

Materials and Methods

Geometric models of femur bone and PFN implants

CT images from an adult male femur were used for the bone model. The patient's data were obtained from the undamaged bone and from the data in the hospital's archive. Radiographic images were obtained using the Siemens Sensation 40 CT (Siemens AG, Munich, Germany) scanner, which has a resolution of 512 x 512 pixels and has 120 kV and 65mAs acquisition values. The slice thickness of the data, which had a total of 665 DICOM radiographic images, was determined as 1 mm and the pixel size was 0.6 mm. The images were processed on Mimics (Materialise, Leuven, Belgium), a medical image processing software, and then converted to NURBS surface form on the Geomagic Design X (3DSystems) software. The proximal femur fracture line was determined as 31-A1 according to the AO Foundation classification. Three different PFN implants were used to fix the ITF line (Figure 1a-1c). Three-dimensional modelling of PFN implants was performed with the help of 3D scanners and digital calipers.

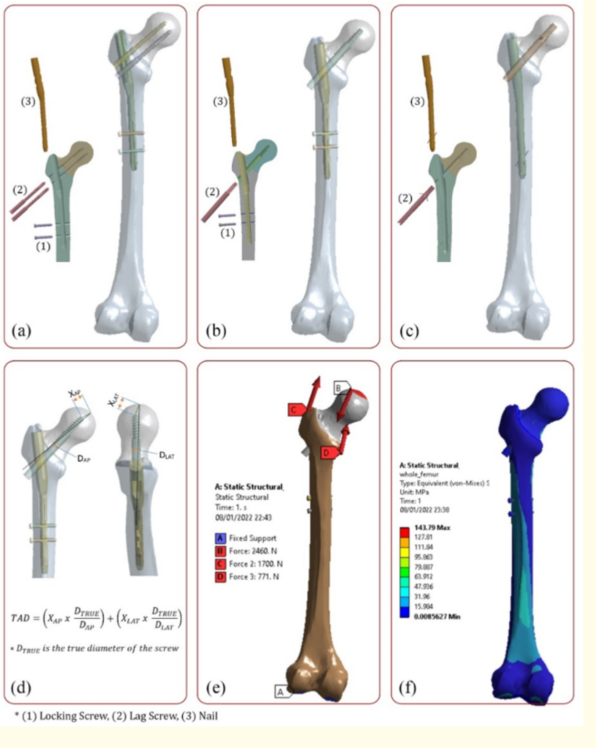

Figure 1: *PFNs using ITF.*

The dimensions of the primitive model shapes on the implants were made with a caliper, and the dimensions of the surfaces that did not have a regular form were made with a 3D scanner. The TAD value has a significant effect on stabilisation of proximal femur fractures fixed with PFN and similar implants [9]. It is known that the fracture line will be adversely affected in cases where the TAD value is less than 20 mm or greater than 30 mm [10]. In this study, therefore, the TAD value for all three PFN implant forms was taken as 25 mm (Figure 1d).

Material properties

The PFN implants and human femoral head model were analysed by the finite element method under specified boundary conditions [11,12]. All components of the femur and PFN systems are defined as a homogeneous, isotropic and linear elastic material, as the aim is comparison of PFN implants. All components of the PFN implants were made of titanium alloy Ti_6Al_4V material. The yield strength of this material, which is defined for implant components, is known to be 885 MPa [13]. The mechanical characteristics of all the components of the PFN implants and femoral bone are given in table 1 [14-16].

Components	Modulus of elasticity (E, GPa)	Poisson's ratio (υ)
Cortical bone	16.8	0.3
Cancellous bone	0.86	0.3
Ti_6Al_4V	114	0.3

***Table 1:** Mechanical properties of PFN implants and femur bone components.*

The density and elasticity modulus values of the cortical and trabecular parts of the femur bone were obtained from the HU values of the bone. HU is a dimensionless value proportional to the degree of attenuation of the X-ray in the medical imaging field. The apparent density () and elasticity modulus () were found by writing the mean HU values obtained through the Mimics program for all components of the femur bone in the places specified in equations (1) and (2) below [17]:

$$\rho = (1.141 * 10^{-3} * HU) + (1.181 * 10^{-1})\ g/cm^3 \qquad (1)$$

$$E\ (MPa) = \begin{cases} 2014 * \rho^{2.5}\ for\ \rho \leq 1.2\ g/cm^3 \\ 1763 * \rho^{3.2}\ for\ \rho \geq 1.2\ g/cm^3 \end{cases} \qquad (2)$$

Material parameters, loading and boundary conditions

All the components of the femur bone and PFN implants were transferred to the ANSYS Workbench 18.2 program, and were then interacted with each other with the Boolean operation (ANSYS Inc.). Four-node tetrahedral elements are used in the mesh structures of the components. All femur components were meshed with a mesh size of 2 mm. In order to preserve the geometric properties of the PFN, the implant components were determined as a mesh size of 1 mm.

During the analysis, the femur bone was restrained from the lateral and medial condyles to prevent rigid body movement of the femur (Figure 2). In the study, the posture of the femur was determined as the stance phase of the gait, taking into account the biomechanical analyses that are frequently made in the virtual environment. The main force (applied to the femoral head at 23° on the frontal and 6° on the sagittal planes) acting on the femoral head was taken as 2460 N. The effect values of the abductor and iliopsoas muscle forces were determined as 1700 N (24° on the frontal and 15° on the sagittal planes) and 771 N (41° on the frontal and 26° on the sagittal planes), respectively [11,12] (Figure 1e). Friction contact was used to define the contact intersections between fractured bone segments, between

PFN implant components, and between bone and PFN implant components. The friction coefficient was set to be 0.46 [18] between fractured surfaces, 0.23 [8] between PFN implant components and 0.3 [19] between bone and PFN implant components.

Results and Discussion

In this study, biomechanical investigation and comparison of three different PFN systems that are frequently used in ITF were performed. The maximum equivalent von Mises stress values occurring on each component are shown in figure 2 visually and graphically. It was observed that the greatest stress value occurred on the PFN body in all three PFN systems. The smallest stress value occurred in the femoral head.

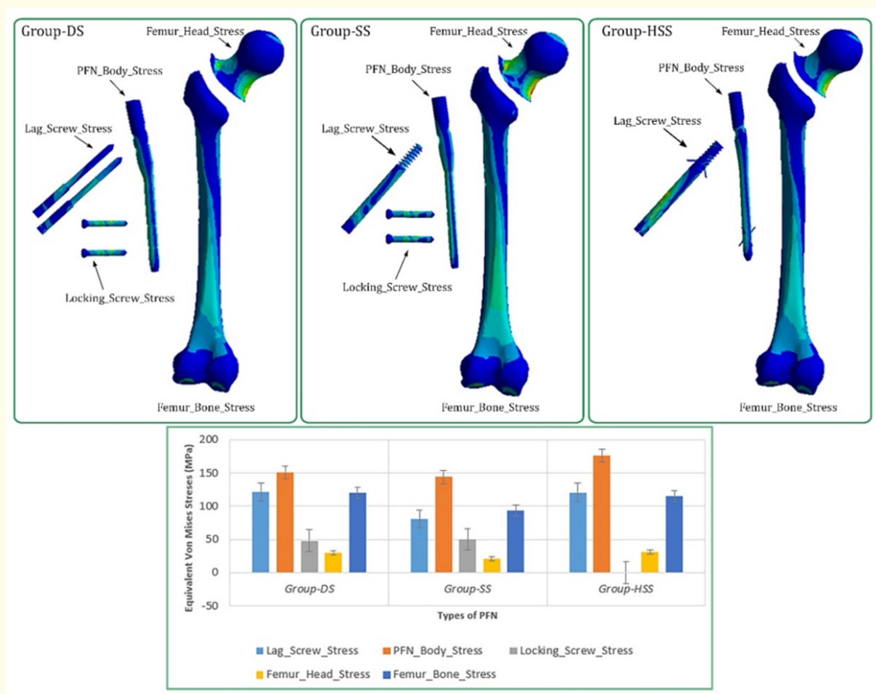

Figure 2: *Equivalent von mises stress analysis results of each component of PFNs.*

When the group-DS, group-SS and group-HSS systems were evaluated, the maximum stress values on the PFNs body of each system were found to be 150.99 MPa, 143.79 MPa and 176.4 MPa, respectively. When the stress concentrations on the PFN bodies were examined, it was seen that the stresses at the transition region of the cross-section dimensions were high. These stress concentrations were observed to progress towards the distal and lag screw regions of the PFN bodies.

The second important component with a high stress concentration in PFN systems was found to be the lag screw. The maximum stress values were found as 121.47 MPa, 80.53 MPa and 120.7 MPa, respectively. It was observed that the stress concentrations progressed from the junction of the lag screw and the PFN body towards the ends. The third component with high stress values was observed as the femur bone. The stress values on the femur bone in the PFN systems were observed as 119.72 MPa, 93.25 MPa and 115.55 MPa, respectively. The stress concentrations on the femur bone were moved from the fracture line to the PFN body and were concentrated in the distal region of the femur bone.

Other important maximum stress values in the PFN systems occurred at the locking screw and femur head. These values were found to be lower than for the other components. Since there is no locking screw on the Group-HSS, this value is indicated as zero on the graph. It is very important to provide the stability of the fracture line with the help of the PFN systems used in the treatment of ITF. Therefore, the pressure and frictional stress on the frictional contact and equivalent von Mises stress values at the fracture line were obtained and are shown in figure 3. From the graph in figure 3, the stress values at the fracture line vary between 10 - 32 MPa. When the stress values were examined, it was observed that they were lower than the PFN and other components of the femur bone. It was observed that the sliding distance on the surfaces was low due to the frictional contact in the fracture line and the frictional stress in this context was between 2 - 4 MPa (Figure 3).

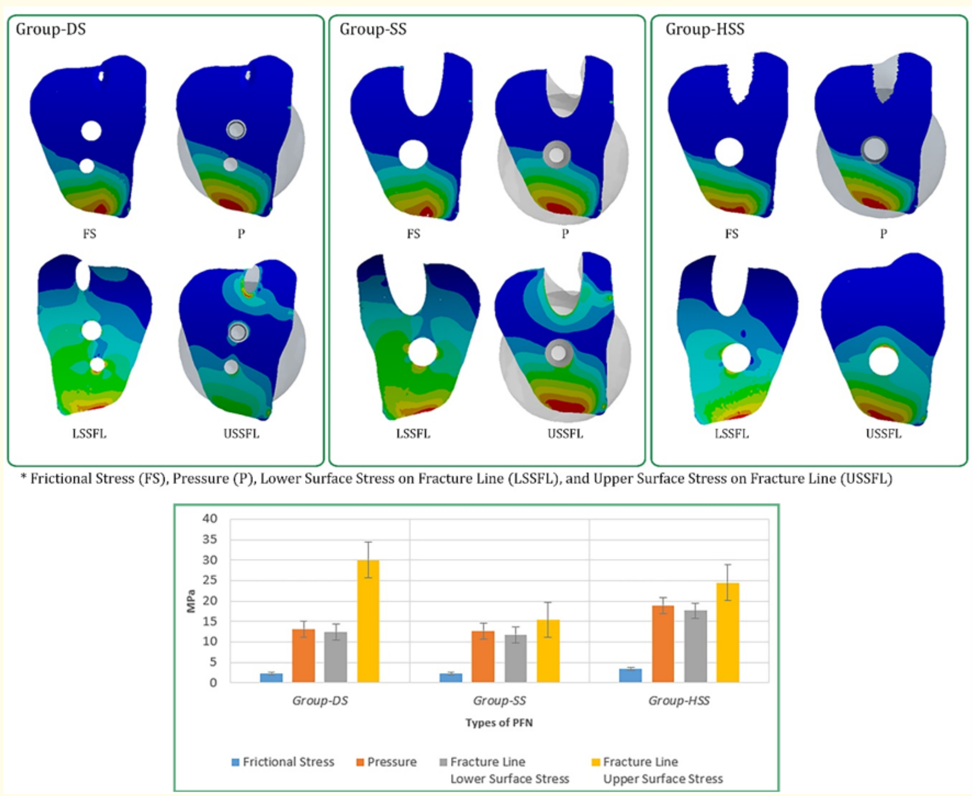

Figure 3: *Stress analysis results on fracture line.*

To evaluate the implants' pull-out values, a displacement test was done 0.5 mm above the femoral neck. According to the test results, the group-DS and group-SS equivalent von Mises stress point was found in proximal screw holes of distal locking as 143.92 and 149.83 MPa consecutively (Figure 4). Group-HSS shows a different stress point in the proximal screw locking hole.

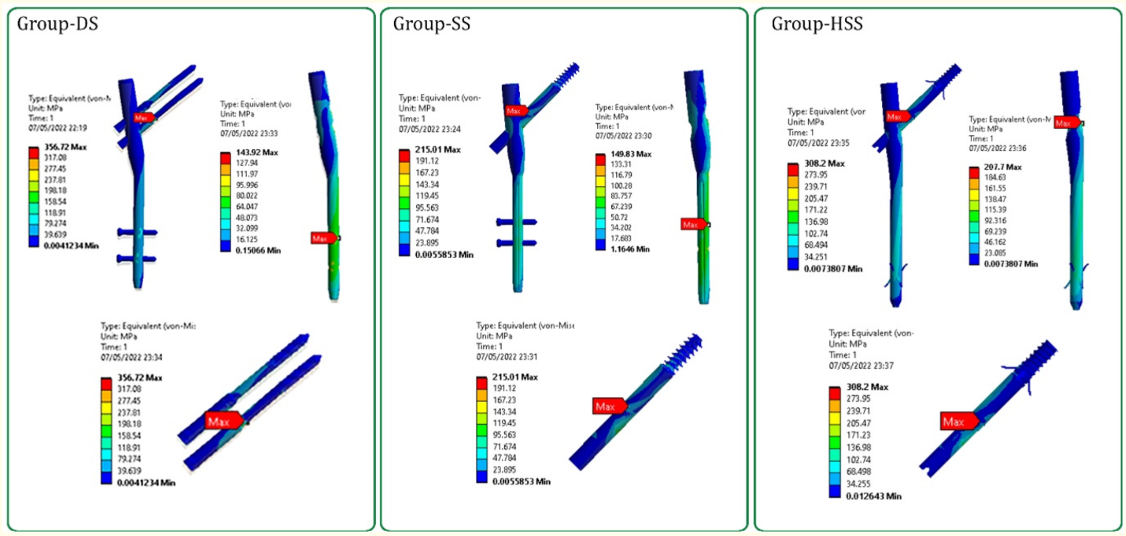

Figure 4: *Stress distributions on PFN bodies as a result of the tensile test.*

When all the PFN bodies were evaluated in all groups, the highest stress values were found on the locking screws. The maximum stress values on the locking screws were obtained as 356.72 MPa (Group-DS), 215.01 MPa (Group-SS) and 308.2 MPa (Group-HSS), respectively.

Intramedullary fixation is the primary surgical treatment for unstable ITF. Group-DS, Group-HSS and Group-SS were newly designed implants and their specifications are different. FE analysis showed that the devices had similar biomechanical effects on the fracture line.

This is mainly due to the structural differences between the single blade, talon blade and the two screws. The Group-DS, consisting of two screws and an intramedullary nail, could share the external loads more effectively. This structure resulted in lower stress on the main intramedullary nail. The distance between the two Group-DS screws was approximately 14.15 mm and the length of the screws was 102.57 mm. For Group-SS the length of the locking screw was 113.84 mm and its diameter was 11 mm, while for Group-HSS the length of the locking screw was 107.5 mm, and its diameter was 11 mm.

According to the screw length, Group-DS provides the largest support area and the diameters of the other screws are the same. For Group-SS the length of the locking screw was the longest. Group-DS could play its role more effectively with the larger support space.

Conversely, the others had to support the same load with a single blade. This would result in higher stress in the main intramedullary nail, which is dangerous for the implant. The overall stability of the Group-SS implant was superior to the Group-DS and Group-HSS fixation (Table 2 and 3).

Furthermore, the stress value of the upper screw (97.7) in the Group-DS model was less than that of its lower screw (121.47 MPa). Wu., *et al*. [20] and Helwig., *et al*. [7] reported the same for A2FN and Targon PF. This could avoid the risk of these screws cutting out of the femoral head. The upper screw could become more likely to loosen and further increase the stress of the lower screw, which might cause medial lateral loosening.

Magnitudes of stress	Group-DS	Group-SS	Group-HSS
Locking screw	121.47	80.53	120.7
PFN body	150.99	143.79	176.4
Lower small screws	48.19	49.99	Not
Femur head	30.04	21.13	31.52
Femur bone	119.72	93.25	115.55

Table 2: *Equivalent von Mises stress values of PFN implant components (MPa).*

	Group-DS	Group-SS	Group-HSS
Frictional stress	2.29	2.25	3.45
Pressure	13.15	12.68	18.92
Stress on lower surface	12.39	11.72	17.63
Stress on upper surface	30.04	15.33	24.51

Table 3: *The significant values on the ITF line (MPa).*

When we compare the frictional stress and pressure on the fracture line, Group-SS has the lowest MPa. Group-DS has two screws and has a similar value. Group-HSS had the highest frictional pressure. This pressure could be related with spikes. When we compare the lower surface stress on the fracture line, Group-SS had the lowest value again. There are some limitations in this study. Firstly, the materials of the cancellous and cortical bones were simplified. The relationship between the density and elastic modulus of the CT in this paper was reported elsewhere [17]. Secondly, this is an experimental analysis with finite element analysis, so clinical studies and a long-term follow-up should be recorded for this group.

Conclusion

The Group-DS, Group-SS and Group-HSS implants have different models. The femur implanted by Group-SS has more stability than the others in the finite element analysis (Table 2 and 3). The stress values in the regions determined on Group-DS and Group-HSS were very close to each other. Therefore, definite judgments cannot be made between them. In all PFN systems, when the body force flow is followed from the femoral proximal head region to the distal condyle region, it is seen that the stress values in places such as the section change region in the PFN body, the junction region of the PFN and Lag screw, and the junction region of the PFN and the locking screw are important (Figure 4). More stable structures can be created by optimizing the geometric forms and locations of these regions. This study can be supported by performing clinical and biomechanical tests of PFN systems in future studies.

Conflict of Interest

Authors declare no conflicts of copyright, financial, consultant, institutional or other resulting in bias.

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