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Does the Proximal Humerus Nail with 2 Distal Screws Provide Sufficient Rotational Stability?

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Background: Proximal humerus nails, frequently used for managing proximal humerus fractures, significantly enhance rotational stability and reinforce fractured fragments. Few research exists regarding the optimal number and positioning of distal screws. This study aimed to assess the stability of diverse screw configurations and scrutinize screw distribution and bone stress via finite element analysis.

Methods: The humerus intramedullary nail (Humerus Interlocking Nail System; TDM) underwent assessment using finite element analysis applied to a humerus model. Three groups were established based on varying distal screw numbers and locations: all 3 distal locking holes were used in group 1; 2 screws (dynamic hole and proximal static hole) in group 2, and 2 screws (dynamic hole and distal static hole) in group 3. Finite element analysis computed stress distribution within the implant and bone for each group. A 1-mm fracture gap was simulated at the surgical neck, and stress distributions were analyzed in both normal and osteoporotic bone models.

Results: Using two screws did not compromise rotational stability. Stress distribution analysis revealed stability across all groups without reaching failure strength. Group 3 exhibited a minor rise in component 11 (direct stress [force per unit area] acting on the positive and negative 1 faces in the 1-axis. direction) and component 22 (direct stress [force per unit area] acting on the positive and negative 2 faces in the 2-axis direction) stress, remaining below failure strength thresholds. Group 1 exhibited the lowest von Mises stress in the nail and screws, while groups 2 and 3 did not reach failure strength levels. Findings remained consistent in the osteoporotic model.

Conclusions: All 3 groups demonstrated rotational stability concerning stress distribution, indicating that using 2 screws for distal fixation does not adversely affect stability. This suggests the potential for saving surgical time and reducing radiation exposure without compromising stability.

Keywords: *Fracture, Humerus, Proximal humerus fracture, Finite element analysis, Intramedullary nail*

Humerus fractures rank as the seventh most prevalent fracture in adults,[1] comprising 4%–5% of all fractures. This fracture type is particularly noteworthy among the elderly, contributing to 10% of all fractures in individuals over 65 years old. Remarkably, it stands as the third most frequent fracture among women aged over 80 years.[2] While intramedullary nails serve as a common modality for achieving union in proximal humerus fractures, few research exists concerning the optimal fixation method for the distal segment. The humerus intramedullary nail, Humerus Interlocking Nail System (TDM), features 1 dynamic hole and 2 static holes designed for distal screws. This configuration allows for 3 distal locking screw options to be utilized.

Numerical analysis employing the finite element analysis (FEA) method is extensively used in the orthope-

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dic domain.[3)] Research involving cadavers or actual bones necessitates substantial costs, prompting our initial exploration using the FEA method. This study leveraged FEA to compute stress distribution in screws and cortical bone holes according to the varying number and placement of distal screws in proximal humerus intramedullary fixation, ultimately verifying stability. Our study aimed to ascertain whether utilizing 2 screws provides adequate stability.

METHODS

The Institutional Review Board waived the requirement for informed consent for this study because it did not involve any human or animal subjects, and thus did not require Institutional Review Board approval.

Methods

Computed tomography scanning with a 1-mm slice thickness was performed on the humerus of a healthy 20-year-old person. A solid model of the humerus was reconstructed using 3D-DOCTOR software (version 18.0, Able Software Corp.) to detect the boundary edge in each slice and Rapidform software (INUS Technology Inc.) to stack the slices and convert the images into an Initial Graphics Exchange Specification-type model. Then, the dimensions were keyed into a computer-aided design (CAD) program (CATIA 2016) to reconstruct 3-dimensional models. The geometrical dimensions of the Humerus Interlocking Nail System (TDM) were obtained from the implant manufacturer's catalog. The geometric model of the humerus and internal fixation were imported into the FEA preprocessing software HyperMesh 18.0 (Altair) to draw the mesh. After the convergence measurement, the mesh size was determined to be 0.5 mm. FEA was performed using MSC-Marc 18.0 (MSC Software Inc.). A geometric model of the implants was assembled as a humerus model (length, 160–200 mm; diameter, 8 mm; and 6 proximal holes and 3 distal holes). The proximal screw holes were unpenetrated and the distal screw holes were penetrated. A 1-mm fracture gap was applied at the surgical neck to model the fracture line of the humeral bone. A fracture gap of up to 1 mm is tolerated, and a transverse osteotomy gap of more than 2 mm reduces healing.[4,5)] Therefore, an osteotomy gap of 1 mm was applied in this study (Fig. 1).

The stress distribution applied to the screws and bone holes was calculated in 3 groups divided according to the number and location: group 1 using all 3 distal locking holes; group 2 using the dynamic hole and the proximal static hole only to fix a total of 2 screws; and group 3 using the dynamic hole and the distal static screw only to fix a total of 2 screws (Fig. 2).

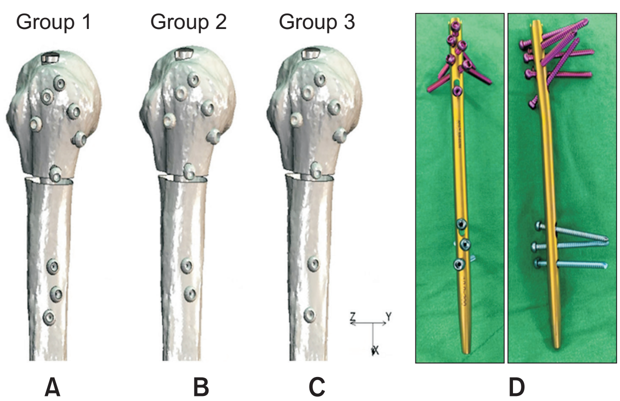

Fig. 2. Three types of distal locking screw fixation. (A) Group 1 is to fix all 3 distal locking holes. (B) Group 2 is to fix the dynamic hole and only proximal static screw. (C) Group 3 is to fix the dynamic hole and only distal static screw. (D) Humerus Interlocking Nail System (TDM).

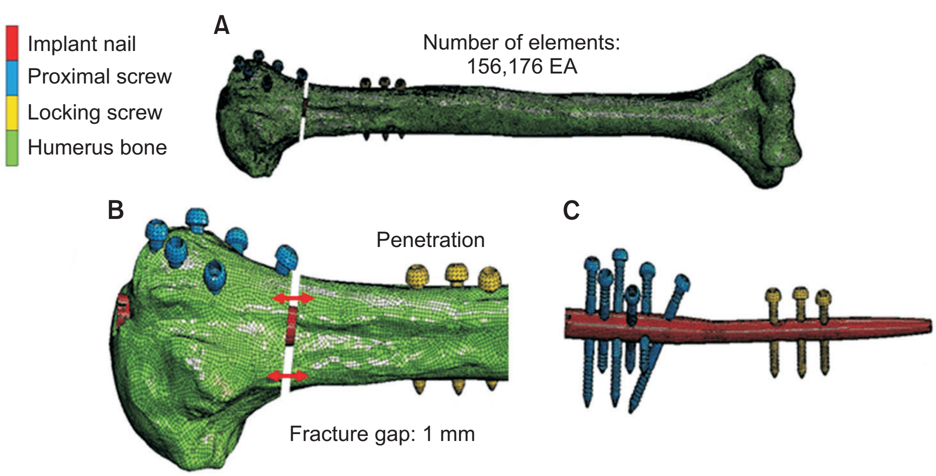

Fig. 1. Finite element analysis model of humerus bone and Interlocking Nail System (TDM). (A) Number of elements. (B) Definition of screws. (C) Interaction of nail and screws.

Materials

Material properties

Materials were assumed to be linearly homogenous, isotropic, and elastic.[6] Although bones are viscoelastic, they are almost always considered elastic because of the relatively low physiologic loading involved.[7] Therefore, most studies have assumed the elasticity of bone, and this study also assumed the same.[8] The heterogeneous properties of the bone were also applied to specific cases, but in most cases, homogeneity and isotropy of the bone were assumed and applied in this study.

The humerus intramedullary nail (Humerus Interlocking Nail System; TDM) was composed of a Ti6Al4V 64 alloy. The material properties of the bony models were obtained from a previous article.[9] The cortical and cancellous bones were assumed to have elastic moduli of 16.7 GPa and 279 MPa, respectively, and Poisson's ratios of 0.3 and 0.34, respectively, were used for normal bone. By applying a 20% reduced value for normal bone quality as an assumption of osteoporotic bone, the elastic moduli of cortical and cancellous bone were modeled at 13.3 GPa and 220 MPa, respectively[10] (Table 1).

Boundary and loading conditions

The attachment muscles of the humeral head shared 6 degrees of freedom in the same center of rotation with the supraspinatus, subscapularis, subscapularis, and teres minor (dx, dy, dz, Rx, Ry, and Rz). Translational and rotational movements were fixed (Fig. 3). Since the bone holes of all screws used for the proximal and distal were fastened by penetration, the screw and bone tying conditions were applied (tied with 6 degree of freedom: dx, dy, dz, Rx, Ry, and Rz). The transepicondylar area, a distal part of the bone, linked 6 degrees of freedom as the center of rotation, and +3,000 N·mm torque was applied in the Rx direction (Fig. 3). The friction coefficient was 0.3 for each bone-implant interaction and implant-implant interaction.[11]

Observation index

To evaluate the failure of the model, the maximum stress values under von Mises stresses were calculated around the proximal and distal locking screws and bone holes in all 3 groups. Maximum stress values of the bone holes under component 11 and 22 stresses were calculated to evaluate the possibility of model failure in the tensile or

Table 1. Material Properties

Material	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Ultimate stress (MPa)	
				Tensile	Compressive
Humerus bone	1,640	16,700	0.30	135	200
Implant (nail, screw)	4,600	113,800	0.34	640	

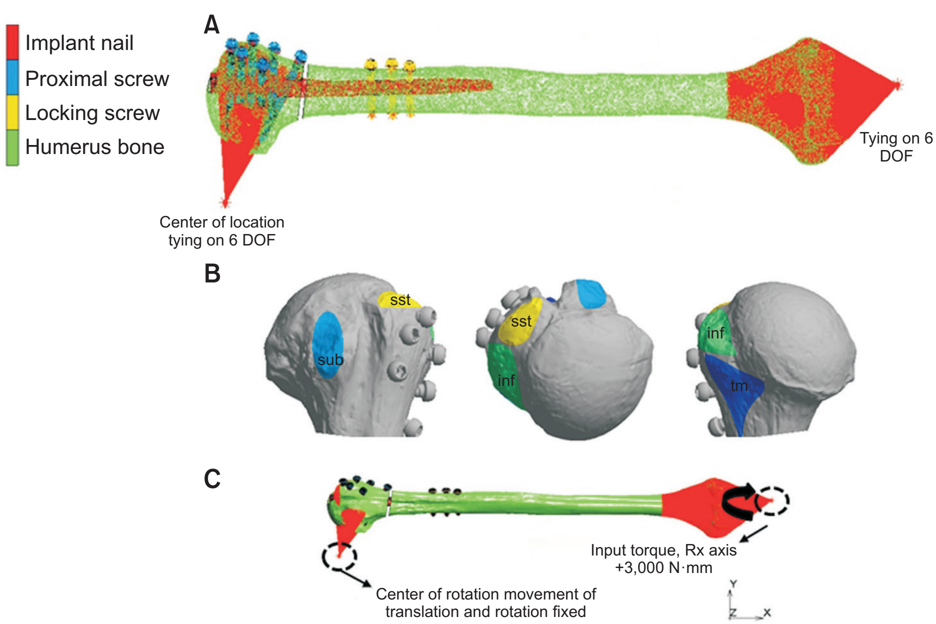

Fig. 3. Definition of tying condition for finite element analysis simulation, boundary, and loading conditions. (A) Interaction of the Humerus Interlocking Nail System with the humerus. (B) Location of rotator cuff muscle on humeral head. (C) Boundary and loading conditions. DOF: degree of freedom, sub: subscapularis, sst: supraspinatus, inf: infraspinatus, tm: teres minor.

compressive direction. Component 11 and 22 stresses were normalized based on the tensile strength of 135 MPa and compression of 200 MPa.

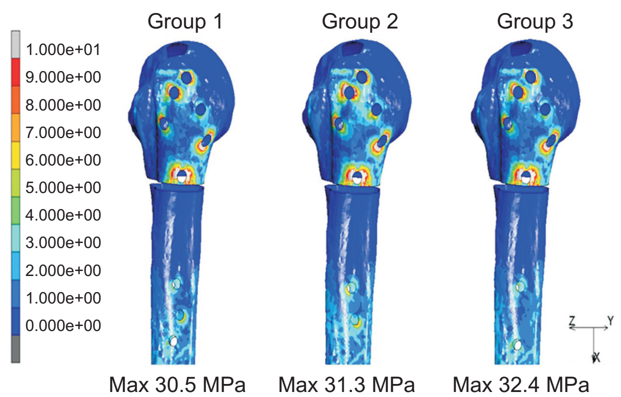

Fig. 4. Distribution of von Mises stress on humerus bone holes in normal bone model.

RESULTS

Stress Distribution for the Normal Bone Model

FEA of the stress changes in the cortical bone holes and screws

The stress distribution according to the screw arrangement was calculated. The maximum von Mises stress in group 1 was 30.5 MPa, group 2 was 31.3 MPa, and group 3 was 32.4 MPa. There were no significant differences between these 3 groups (Fig. 4). In the stress of component 11 (longitudinal direction), the tensile strength of each group was 25.4, 26.2, and 26.8 MPa, respectively, and the compressive strength was 33.9, 34.9, and 36.0 MPa, respectively, so there was no difference (Fig. 5A). Component 22 (transversal direction) stress showed no difference in transversal direction stress as tensile strength was 21.2, 22.7, and 22.9 MPa in each group, and compressive strength was 30.9, 27.2, and 31.7 MPa, respectively (Fig. 5B). The distal screw

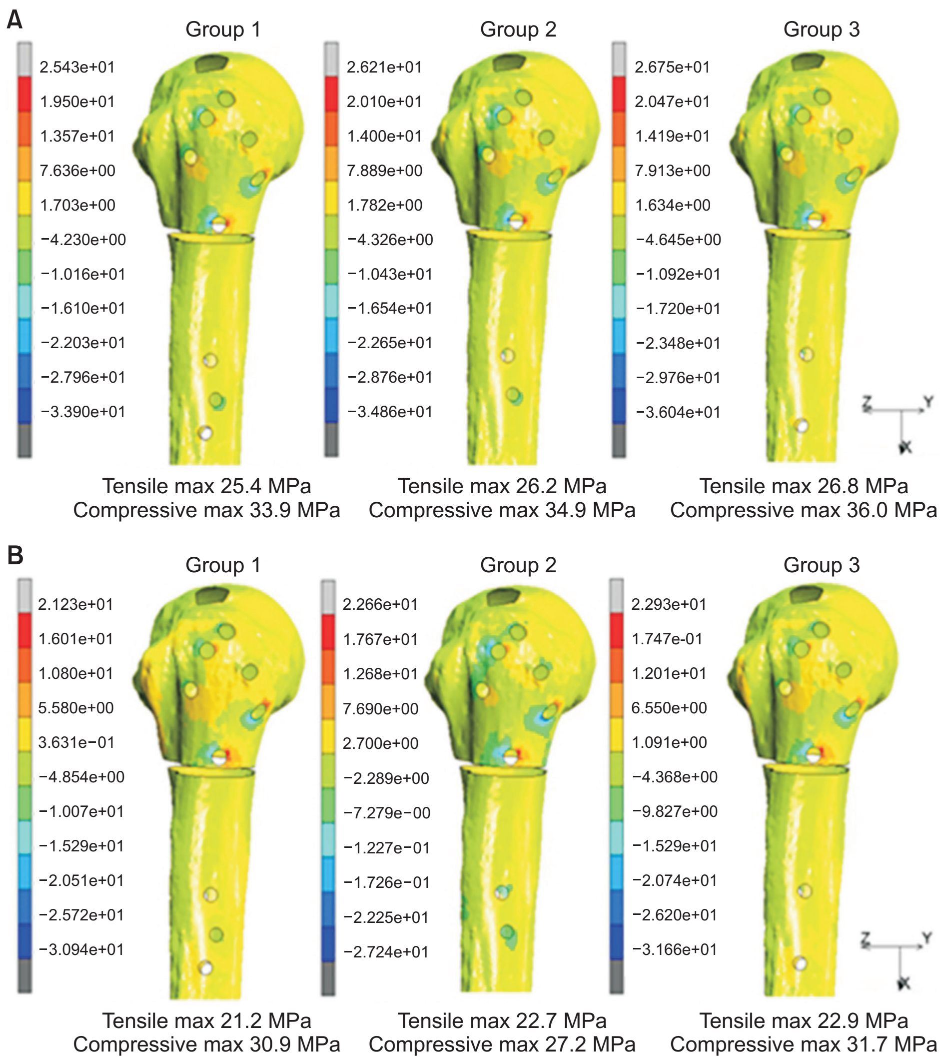

Fig. 5. Distribution of component 11 and 22 stresses on the humerus bone holes in normal bone model. (A) Component 11. (B) Component 22.

number and location will not affect the stability of the bone. It was indirectly proved that it is possible to fix the distal screw with only 2 screws.

FEA of the stress changes in the nail, screws, and nail screw connection

As a result of the stress distribution applied to the nail and screw, the maximum von Mises stress was 292.9, 280.9, and 340.9 MPa in groups 1, 2, and 3, respectively. The equivalent stress distribution was similar, and a 10% increase was shown in group 3, but the effect was not significant to the extent that failure load was not reached. In the region of the proximal screw, all groups showed 86.8, 88.2, and 86.8 MPa, respectively. In the locking screw area, 53.9, 70.4, and 69.8 MPa were shown, respectively. In the case of the screws in the proximal part, the stress was uniformly generated, and there were no significant differences between these 3 groups. In the distal screws part, the stress was the lowest in group 1, but compared to the other 2 groups, the stress was not enough to lead to failure. All 3 groups were stable (Figs. 6-8).

Stress Distribution for the Osteoporotic Bone Model

FEA of the stress changes in the cortical bone holes and screws

As a result of the stress distribution according to the screw arrangement in the osteoporotic bone with the elastic modulus reduced by 20%, the maximum von Mises stress

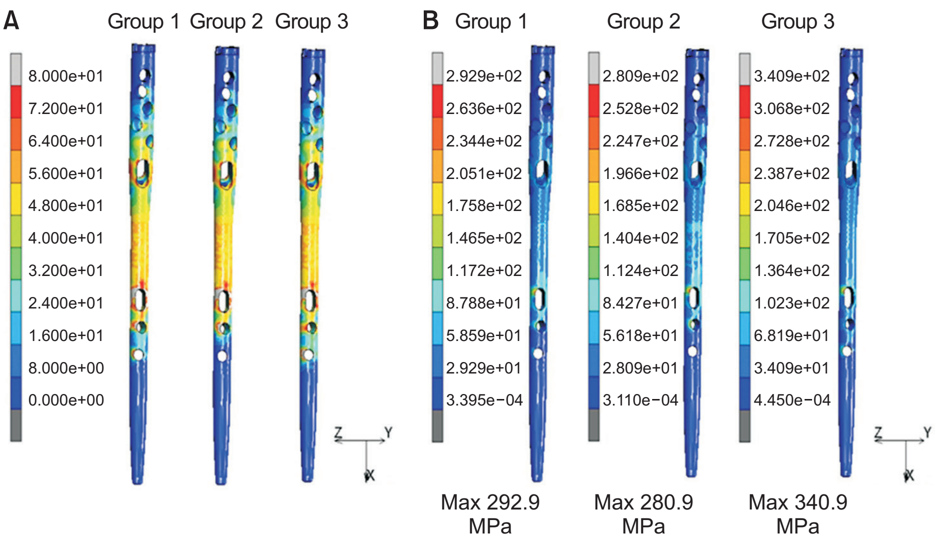

Fig. 6. Distribution of von Mises stress on the nail in normal bone. (A) Equal contour range. (B) Relative contour range.

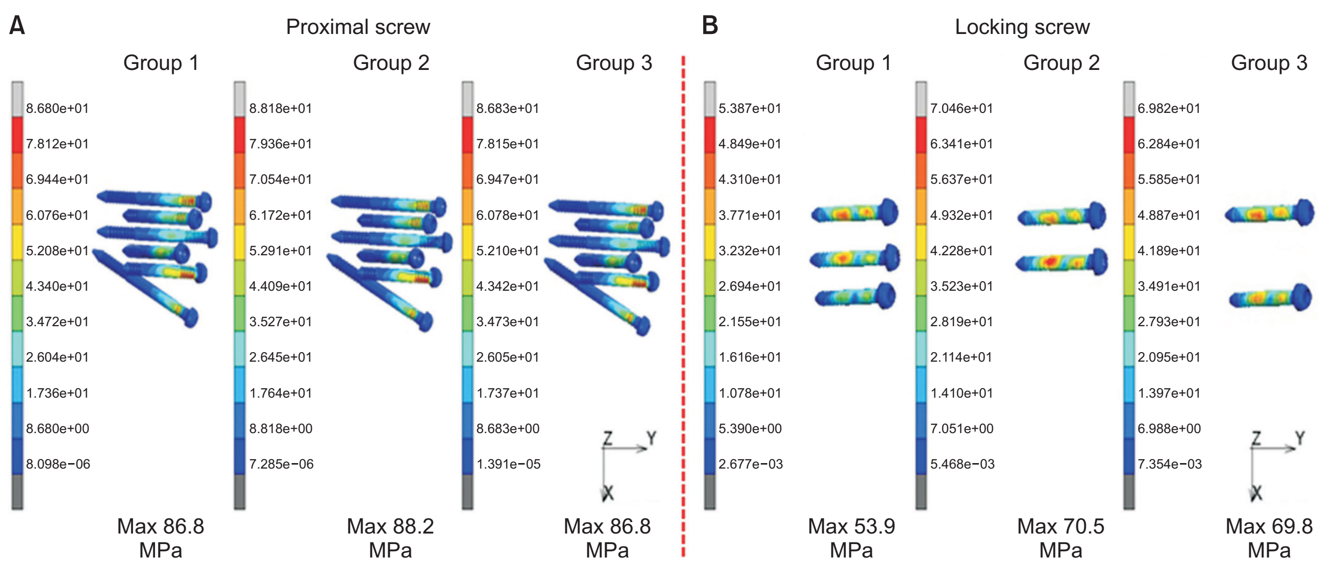

Fig. 7. Distribution of von Vises stress on screw in normal bone model. (A) Proximal screws. (B) Locking screws.

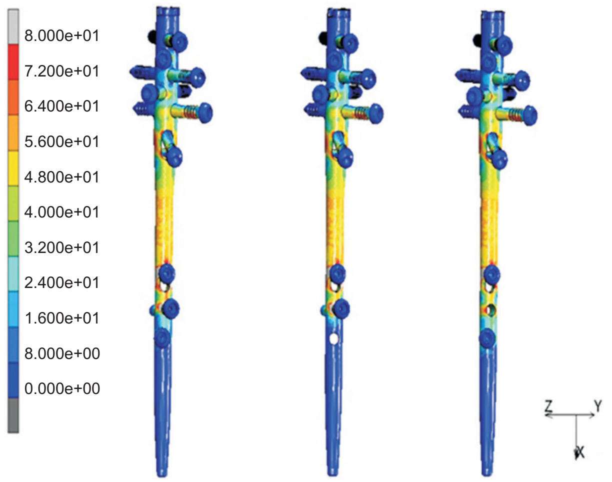

Fig. 8. Distribution of von Mises stress on the nail and screw combination in normal bone model.

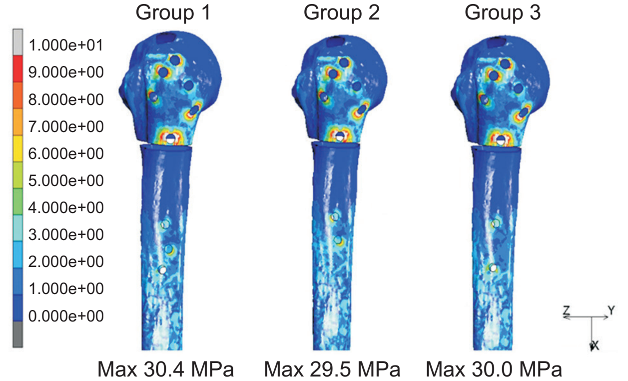

Fig. 9. Distribution of von Mises stress on the humerus bone holes in osteoporotic bone model.

might be smaller than 30.4 MPa in group 1, 29.5 MPa in group 2, and 30.0 MPa in group 3 (Fig. 9). In the osteoporotic bone, the effect of screw placement and the number of screws did not have significant difference.

FEA of the stress changes in the nail and screws, and nail screw connection

As a result of the stress distribution applied to the nail and screw, the maximum von Mises stress was 288.2, 283.3, and 327.5 MPa, respectively, in group 1, group 2, and group 3, like the stress distribution results in the normal bone. The maximum von Mises stress was 84.6, 84.0, and 87.5 MPa, respectively, in the region of the proximal screw and 53.7, 74.1, and 63.5 MPa, respectively, in the region of the distal screw. The stress distribution was the lowest in group 1 of the distal screw region, but there was no significant difference compared to that in the other 2 groups (Figs. 10 and 11).

DISCUSSION

In our study, using 2 distal screws demonstrated comparable rotational stability to using 3 screws in proximal humerus shaft fractures. Only a few studies addressed the optimal number of distal screws in long nails used for long bone fractures, such as those in the tibia and femur. Regarding tibia shaft fractures, a comparison between using 2 versus 3 distal screws revealed no statistically significant difference.[12] It was suggested that fixation with only 2 screws was sufficient. In femur fractures, studies have shown no significant clinical or radiological discrepancy when comparing the dynamic locking and unlocking of distal screws.[13]

In our study, group 1 exhibited the most favorable outcome, displaying the lowest stress levels and superior stability across all bone holes, nails, proximal screws, and distal screws. In the normal bone model, group 2 revealed elevated stress levels on distal screws; in the osteoporotic bone model, group 3 exhibited increased stress on distal screws. Throughout all groups, stress levels remained below the threshold of failure strength (Table 2). Hence, it can be inferred that stability was maintained across all groups.

Regarding the use of 2 distal screws, our results suggest a preference for using distal static screws in the normal bone model (group 3). In the assumed osteoporotic bone model, using proximal static screws (group 2) may be more favorable. Rotational stress, a significant factor affecting the humerus, was a predominant focus in our study, and the results were in line with previous findings.[14] Our study systematically varied the number and location of screws, enabling the calculation of resultant stress on individual screws and bone holes (Table 2).

Recent reviews have highlighted iatrogenic nerve injury rates ranging from 4% to 32% in cases involving plate fixation or intramedullary nailing.[15] Altering the number or location of screws could potentially decrease the risk of nerve damage further.[15,16] In proximal femoral nailing procedures involving a distal locking screw, there are reports of increased radiation exposure by approximately 12 minutes.[17] Such findings emphasize the importance of optimizing screw configuration to minimize the associated risks and complications during surgical interventions. Surgeries for humeral shaft fractures using nailing were found to have a longer operating time (74–87 minutes) and increased fluoroscopy exposure (59–100 seconds) when distal locking screws were used, compared to cases

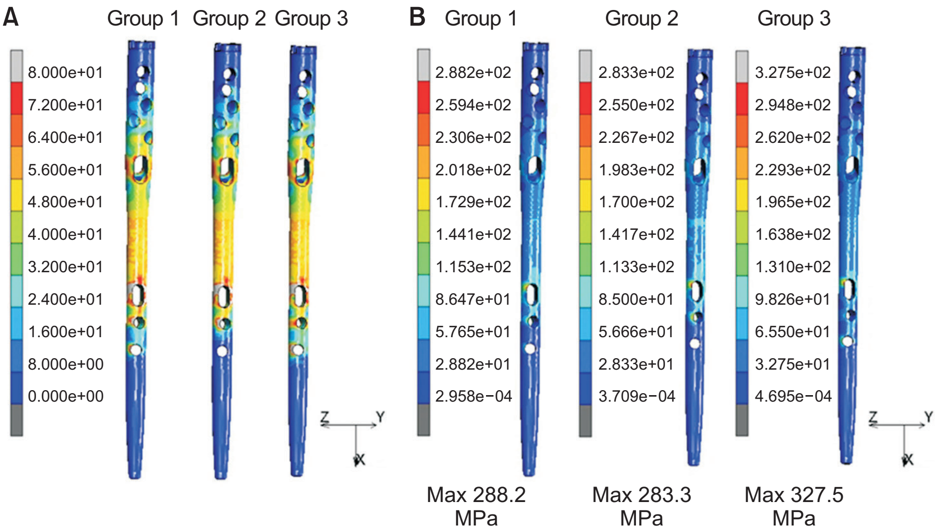

Fig. 10. Distribution of von Mises stress on nail in osteoporotic bone model. (A) Equal contour range. (B) Relative contour range.

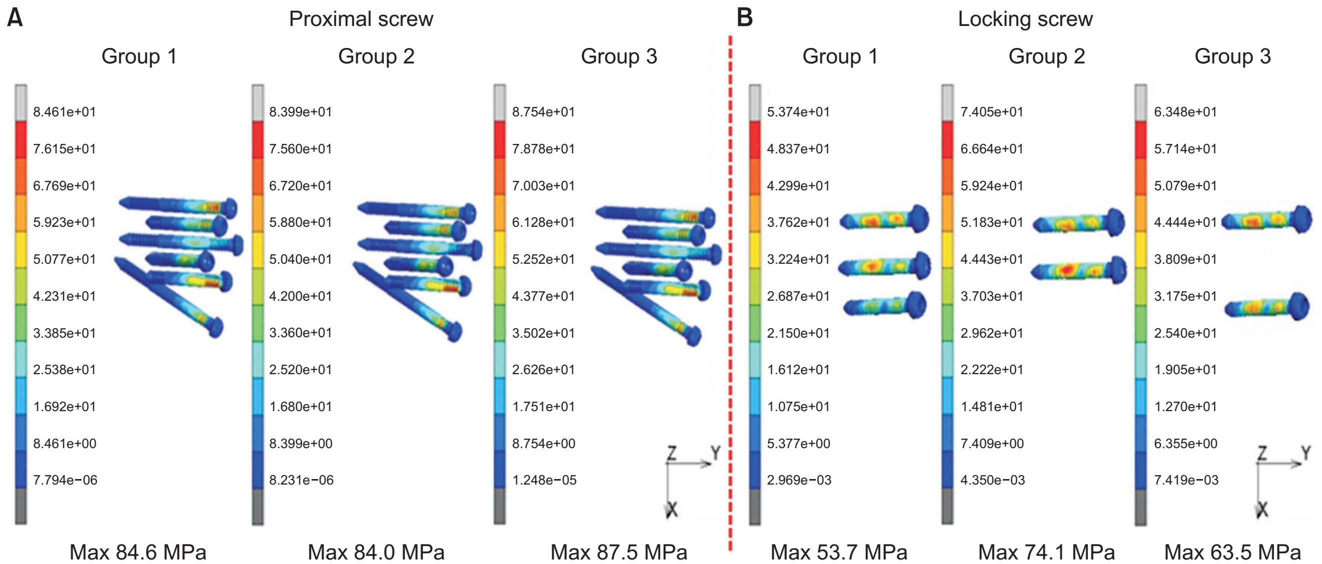

Fig. 11. Distribution of von Mises stress on the screw in osteoporotic bone model. (A) Proximal screws. (B) Locking screws.

Table 2. Comparison of Maximum von Mises Stress on the Bone Models and Implants

Material property	Case	Maximum von Mises stress			
		Humerus bone	Implant nail	Proximal screw	Distal screw
General bone model material	Group 1	30.5	292.9	86.8	53.9
	Group 2	31.3	280.9	88.2	70.5
	Group 3	32.4	340.9	86.8	69.8
20% Down bone model material	Group 1	30.4	288.2	84.6	53.7
	Group 2	29.5	283.3	84.0	74.1
	Group 3	30.0	327.5	87.5	63.5

All of the bone, nail, proximal, and distal screws did not reach ultimate strength.

without distal locking.[18] Although many cases of exposure to such excessive radiation are often overlooked, the relative risk of cancer among orthopedic surgeons exposed to higher radiation than the general population is 5.37.[17]

Our study has some limitations. FEA is completely virtual and introduces simplification in all aspects. Boundary conditions become difficult to handle owing to the anatomical realistic structure and motion of the shoulder joint.[19] It is impossible to simulate the real boundary conditions with all the muscles, tendons, ligaments, and bones acting together. These material properties are not standardized, so it is difficult to accurately reproduce or verify experiments. In this study, a simple 2-part fracture was assumed. Future studies assuming more complex fractures will be needed. Most of the FEA research was fundamental rather than clinical research. Therefore, individual interpretation is required for clinical application.

In proximal humerus nails, stress distribution displayed stability across von Mises stress, longitudinal, and transversal directions within bone holes, nails, and both proximal and distal locking screws. In the case of distal screws within the proximal humerus nail of a normal bone, the application of solely 2 screws did not compromise stability. In osteoporotic bones, the fixation of 2 distal screws is not anticipated to impact stability.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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