



A biomechanical analysis of intramedullary nailing for humeral shaft fractures using 3D-finite element method

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Background: Intramedullary nailing by antegrade and retrograde technique was introduced in humeral shaft fractures after interlocking nailing of femoral and tibial fractures achieved excellent results. The aim of this study was to evaluate biomechanical properties of antegrade and retrograde nailing in diaphyseal fractures according to levels of the humerus.

Methods: To estimate and compare biomechanical stability of antegrade and retrograde nailing, 3D geometrical and finite element method (FEM) models of the humeral fractures and intramedullary nails were formed using Solidworks software, based on CT scans of the humerus and analyzed with ANSYS 15.0 program. Biomechanical analysis was performed under three types of loads: anterior-posterior (AP) bending, torsion and axial compression.

Results: The bending properties of antegrade nailing were higher than those of retrograde nailing in any site of the humeral shaft fractures. During the testing under torsion, antegrade nailing showed that the displacements of fracture sites were lower compared to those retrograde nailing in the proximal and distal diaphyseal fractures. Under axial compression, antegrade intramedullary nailing demonstrated that the stiffness and displacement were found to be lower than those by retrograde nailing in the distal shaft of the humerus and there were no significant differences in stiffness and displacement between antegrade and retrograde nailing in the proximal diaphyseal and midshaft fractures.

Conclusions: For the proximal and distal shaft fractures of the humerus, the stability of antegrade nailing was higher than the stability of retrograde nailing. In the midshaft fractures of the humerus, there was no biomechanical difference between antegrade and retrograde technique.

Keywords: Nailing; finite element method (FEM); displacement; stiffness

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Introduction

It is widely accepted that acute fractures of the humerus have a good healing tendency by conservative treatment, because of an excellent blood supply to the bony fragments by the surrounding muscles (1-4). Conservative treatment, however, has limitations in cases of radial nerve palsy,

extensive soft-tissue injury, multiple fractures, delayed union or nonunion, non-compliance or obesity (5,6). Plate osteosynthesis has been the treatment of choice when surgical procedure is needed (7,8).

Humeral locking nails were introduced to reproduce the success seen with similar devices used in the lower extremities. Even though advantages of interlocking nails

Table 1 Young's modulus and poisson ratio of the humerus

Compartment	Young's modulus (Kgf/cm ²)	Poisson ratio
Humerus	17,000	0.30
Nickel	2,100,000	0.31

compared with plating included less soft tissue damage, closed reduction and periosteum-sparing stabilization of complex fractures, these theoretical advantages were not confirmed and severe complications such as shoulder pain, delayed union, non-union and iatrogenic fractures were reported (5). Meanwhile, the decision on whether an antegrade or retrograde nailing is performed was left to the discretion of the surgeon (9). Authors reported that healing of acute humeral shaft fractures was not correlated to the direction of nailing (10,11), but in our experience, fracture healing was dependent upon choice of nail insertion according to the fracture sites of the humerus. In addition, to the knowledge of the authors no clinical and biomechanical results have been regarding the bone healing on the direction of interlocking nailing in the proximal, midshaft and distal diaphysis of the humerus. Hence the purpose of this study was to analyze the biomechanical properties of antegrade and retrograde nailing under three types of loads [axial compression, anterior-posterior (AP) bending and torsion] in diaphyseal fractures according to levels of the humerus.

Methods

Based on the geometrical configurations and Unreamed Humeral Nails and CT scans of the humerus, 3D geometrical and finite element method (FEM) models of antegrade and retrograde nailing with humeral shaft fractures were formed by using Solidworks software. With ANSYS 15.0 program, the model was meshed into 6,042 pieces of parabolic tetrahedron elements. By combining these models, interlocking nailing of the humeral shaft fracture was modeled, which consisted of fractured humerus, intramedullary nail and interlocking screws. The mechanical values which were inputted to this FEM model are as follows (Table 1).

To conduct finite element analysis, it was supposed that antegrade and retrograde nailing with double interlocking screws insertion in each fragment was undergone respectively in the proximal, distal shaft and midshaft of the humerus of a person; 39 years old, 1.72 m tall and 60 kg

weighted.

While the proximal end of the humerus was being constrained, bending force was applied to the fracture site by 5 N, for torsional testing, rotational moment of 0.1 Nm was applied to the distal end of the humerus and axial compression was transmitted through the distal end by 100 N.

According to antegrade and retrograde technique, values of stiffness and displacement at the fracture sites and the humerus were obtained.

Results

Bending properties

During the testing under AP bending, the values of stiffness (Figures 1,2) and displacement (Figures 3,4) at the fracture site and the humerus are as follows (Table 2).

Compared values of fracture bending stiffness by antegrade nailing with those by retrograde nailing according to fracture levels under bending force, the value of antegrade technique in proximal shaft was lower than the value of retrograde. Also, antegrade nailing demonstrated less stiffness than retrograde nailing, but the difference was not found to be great. In addition to the values of fracture bending stiffness, maximum stiffness values of the humerus had a similar tendency to those.

From the viewpoint of displacement, the value of fracture site produced in antegrade approach by bending force was considerably lower than the value in retrograde nailing in the proximal diaphysis. Displacements in the midshaft and distal diaphysis were not different between the nailing directions. Maximum and minimum values of the humerus were found to be as well as the values of fracture site.

Torsional properties

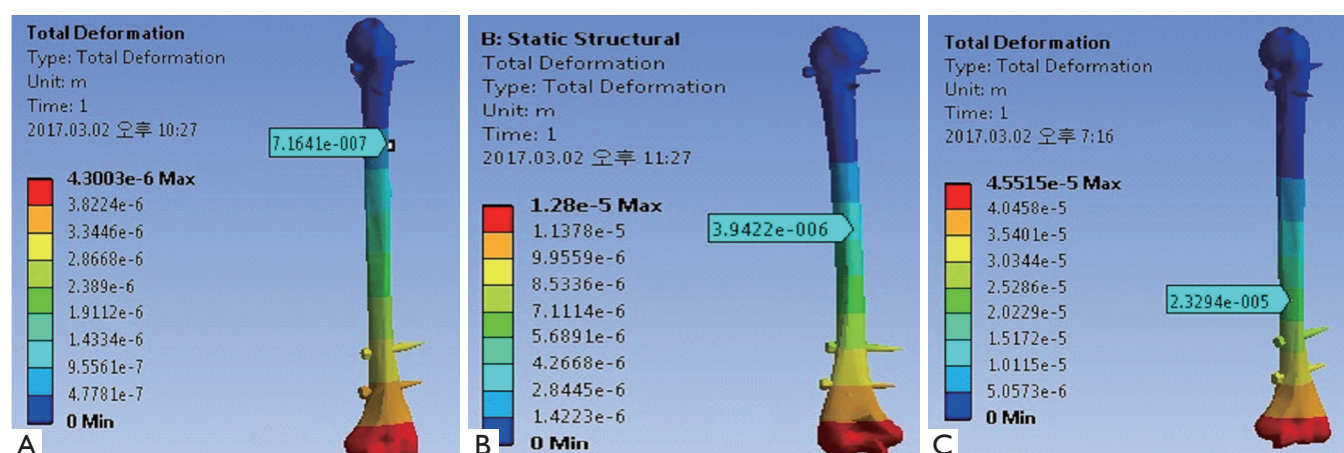
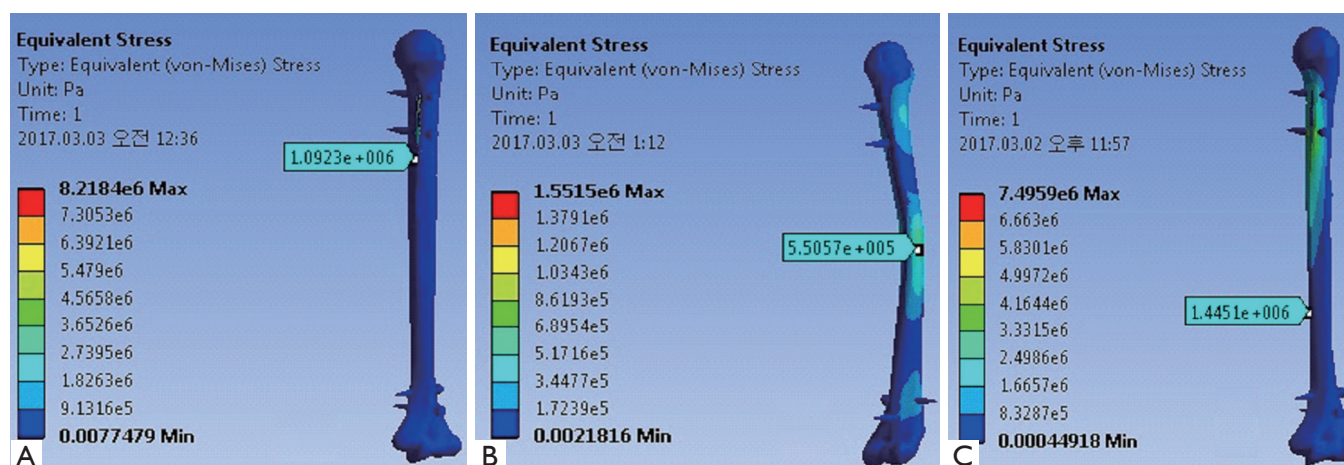
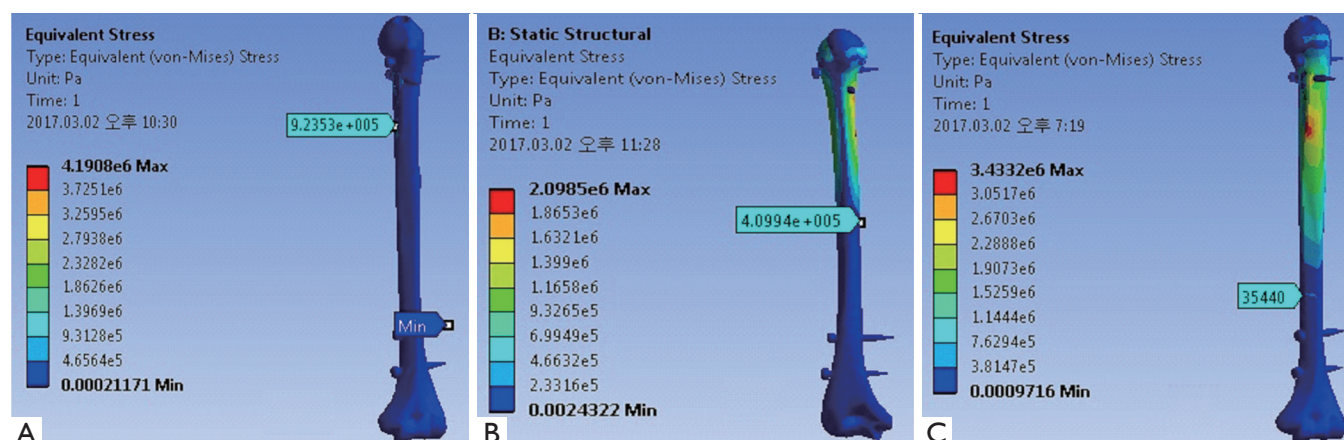
Table 3 presents the results of testing under torsion.

The values of fracture torsional stiffness in antegrade nailing in the proximal, distal diaphysis and midshaft were somewhat greater than in retrograde technique, but the maximum values were not great on the contrary (Figures 5,6).

Antegrade nailing resulted in less displacements of fractures site during torsional testing in the proximal and distal diaphysis than retrograde nailing (Figures 7,8).

Axial compression properties

As described in the Table 4, in the distal shaft, the value



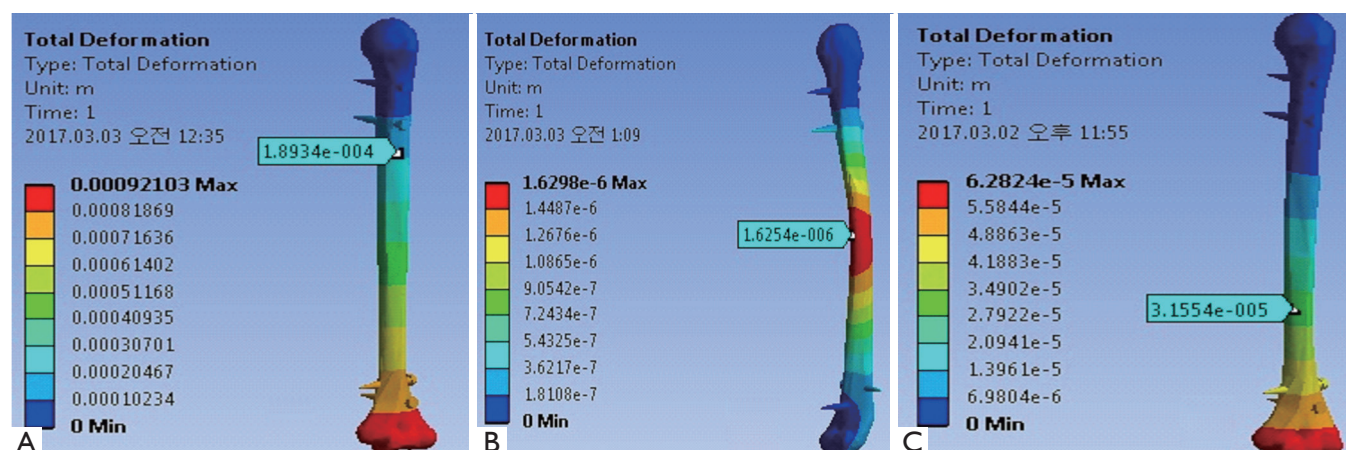


Figure 4 Bending displacement of retrograde nailing. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

Table 2 Values of stiffness and displacements under bending loads

Biomechanical properties	Antegrade technique (fracture site)			Retrograde technique (fracture site)		
	Proximal diaphysis	Midshaft	Distal diaphysis	Proximal diaphysis	Midshaft	Distal diaphysis
Displacements at the fracture site (m)	7.164×10^{-7}	3.9422×10^{-6}	2.329×10^{-5}	1.8934×10^{-4}	1.6254×10^{-6}	3.1552×10^{-5}
Fracture stiffness (Pa)	9.235×10^5	4.099×10^5	35,440	1.0923×10^6	5.5027×10^5	1.4451×10^6
Maximum stiffness (Pa)	4.19×10^6	2.098×10^6	3.433×10^6	8.218×10^6	1.5515×10^6	7.4959×10^6
Minimum stiffness (Pa)	0.00021	0.00024	0.00097	0.0077	0.00218	0.0004
Maximum displacements (m)	4.3×10^{-6}	1.28×10^{-5}	4.55×10^{-5}	0.00092	1.6298×10^{-6}	6.2824×10^{-5}
Minimum displacements (m)	4.778×10^{-7}	1.4223×10^{-6}	5.057×10^{-6}	0.0001	1.8×10^{-7}	6.98×10^{-6}

Table 3 Values of stiffness and displacements during torsion

Biomechanical properties	Antegrade technique (fracture site)			Retrograde technique (fracture site)		
	Proximal diaphysis	Midshaft	Distal diaphysis	Proximal diaphysis	Midshaft	Distal diaphysis
Displacements at the fracture site (m)	2.685×10^{-7}	3.4×10^{-7}	1.4544×10^{-6}	3.1596×10^{-5}	1.578×10^{-7}	1.3952×10^{-5}
Fracture stiffness (Pa)	5.321×10^5	7.5429×10^5	5.97×10^5	56890	1.044×10^5	5.246×10^5
Maximum stiffness (Pa)	3.3759×10^6	1.303×10^6	3.8833×10^6	6.956×10^6	2.627×10^6	3.583×10^6
Minimum stiffness (Pa)	0.0115	0.0126	0.0259	0.0026	0.00229	0.0103
Maximum displacements (m)	5.5264×10^{-6}	2.2062×10^{-6}	9.925×10^{-6}	0.0004	1.267×10^{-6}	5.648×10^{-6}

of fracture site stiffness by antegrade nailing under axial compression was lower than the value by retrograde technique. Also, retrograde nailing showed less stiffness

than antegrade nailing in the proximal diaphysis and midshaft, but there was no significant difference between them. Maximum stiffness values of antegrade nailing in the

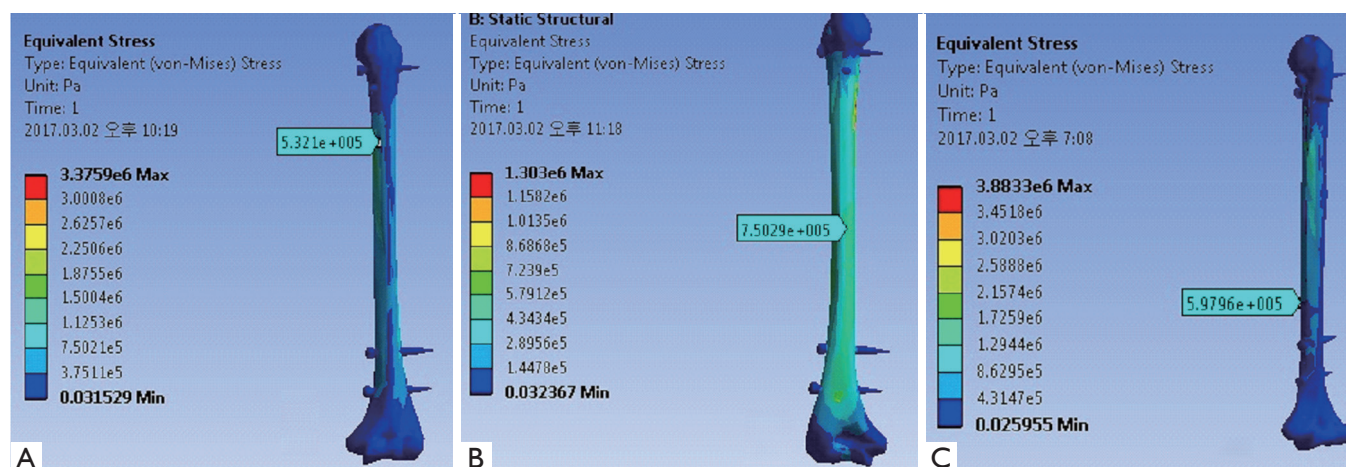


Figure 5 Torsional stiffness of antegrade nailing. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

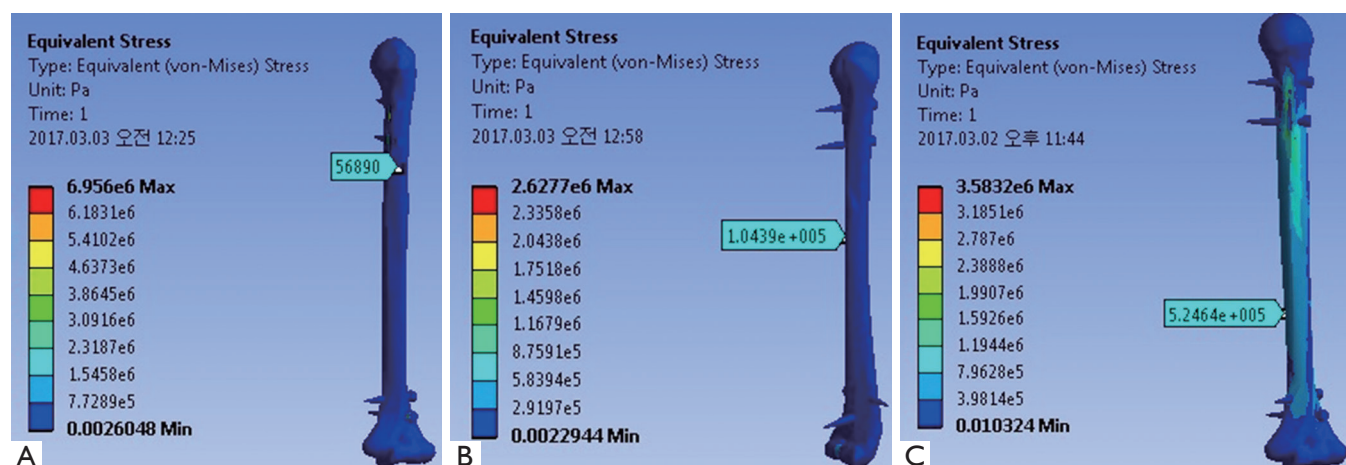


Figure 6 Torsional stiffness of retrograde nailing. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

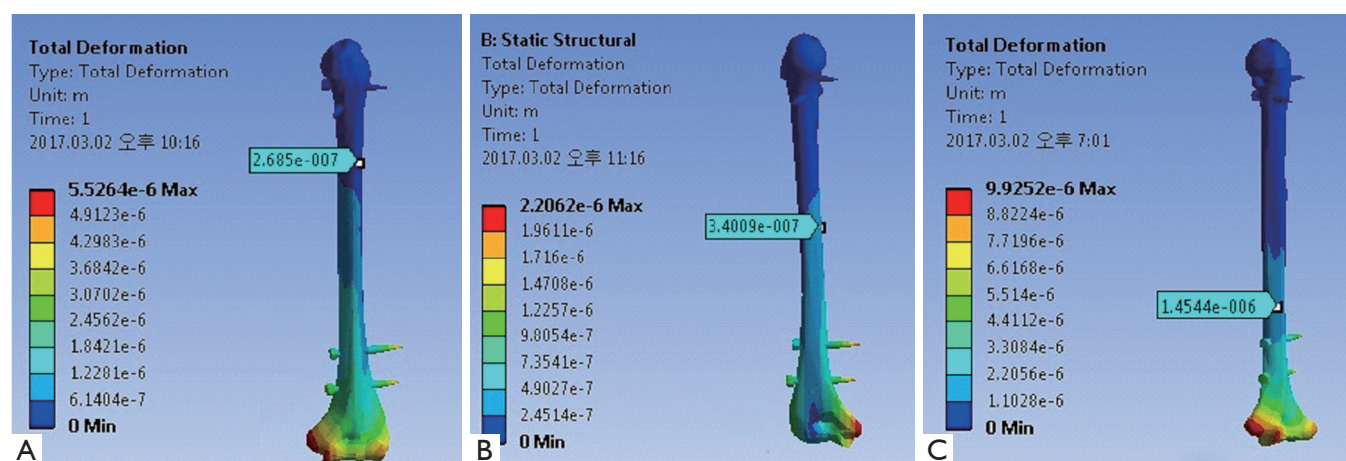


Figure 7 Torsional displacement of antegrade nailing. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

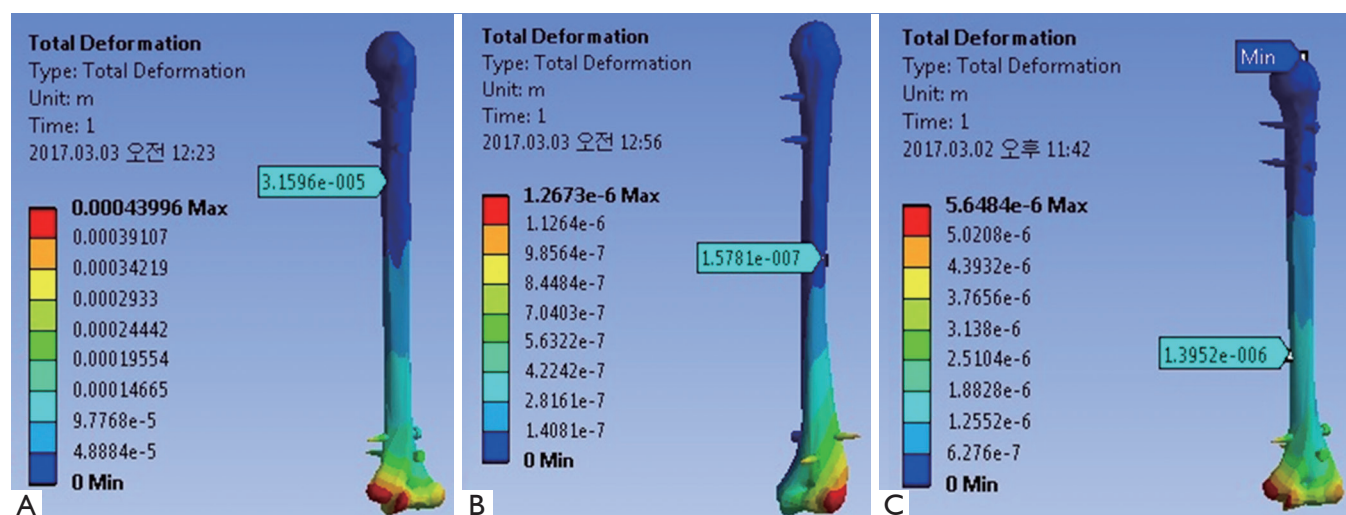


Figure 8 Torsional displacement of retrograde nailing. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

Table 4 Values of stiffness and displacements during axial compression

Biomechanical properties	Antegrade technique (fracture site)			Retrograde technique (fracture site)		
	Proximal diaphysis	Midshaft	Distal diaphysis	Proximal diaphysis	Midshaft	Distal diaphysis
Displacements at the fracture site (m)	2.05×10^{-5}	9.02×10^{-5}	1.442×10^{-6}	7.4512×10^{-6}	8.5962×10^{-5}	4.617×10^{-5}
Fracture stiffness (Pa)	7.84×10^6	4.26×10^6	2.69×10^5	7×10^6	4.1×10^6	3.19×10^6
Maximum stiffness (Pa)	1.085×10^7	6.45×10^6	6×10^6	1.11×10^7	2×10^7	8.95×10^6
Minimum stiffness (Pa)	0.0419	0.0341	0.0012	0.009	0.0094	0.0042
Maximum displacements (m)	6.115×10^{-4}	5.43×10^{-4}	1.53×10^{-6}	1.229×10^{-4}	4.653×10^{-4}	1×10^{-4}
Minimum displacements (m)	6.79×10^{-5}	6×10^{-5}	1.7×10^{-7}	1.36×10^{-6}	5.17×10^{-5}	1.178×10^{-5}

proximal, distal diaphysis and midshaft were lower than retrograde nailing (*Figures 9,10*).

Displacements of fracture site and maximum displacements had a similar tendency to the stiffness on axial compression (*Figures 11,12*).

Discussion

Conservative treatment is indicated in undisplaced fractures, if patients refuse operative stabilization and in patients with indication for surgery. Plating is frequently used for metaphyseal fractures or fractures with an extension into the joint. External fixation is seldom used. The main indications are severe soft tissue injuries, severe contamination and infection (12,13). After soft tissue healing, conversion to

definitive internal fixation is planned (14).

Double interlocking on either fragment of the fracture provides higher axial and rotator stability than single interlocking. Interlocking through slots is less stable than through round static holes (15).

The choice of an antegrade or retrograde approach was dependent on the preference of the surgeon. Healing of acute humeral shaft fractures is independent of the direction of nailing (10,11).

In our experience, however, fracture healing was different between antegrade and retrograde nailing according to the fracture levels. For example, a patient with the distal shaft fracture of the humerus was operated with a retrograde nailing, which resulted in nonunion after 6 months and reoperated with a plate osteosynthesis (*Figure 13*). Hence,

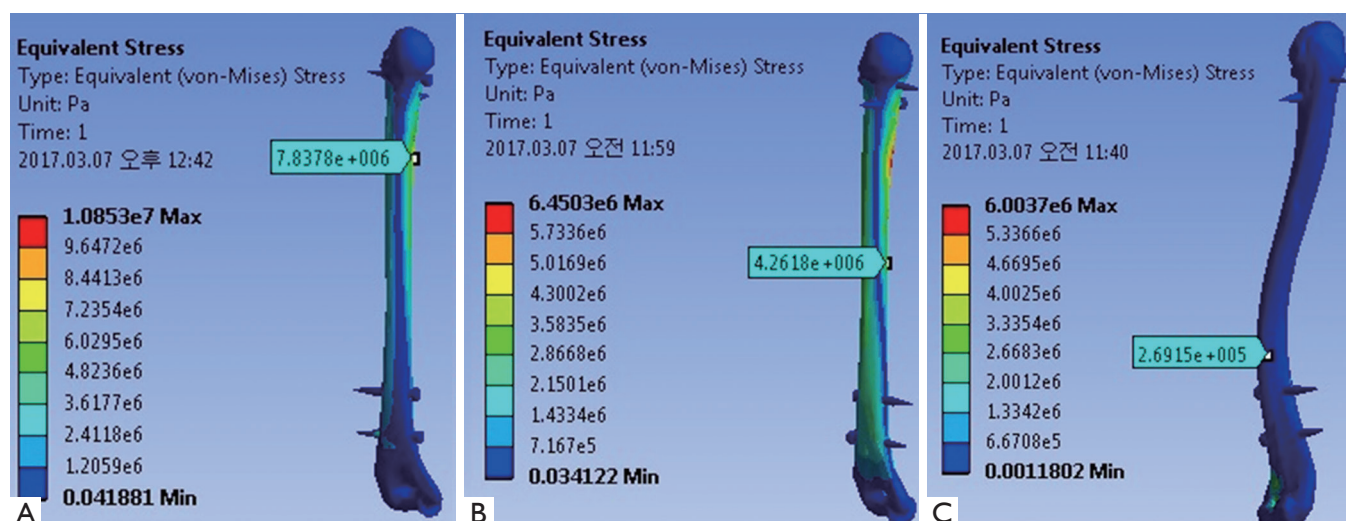


Figure 9 Stiffness of antegrade nailing on axial compression. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

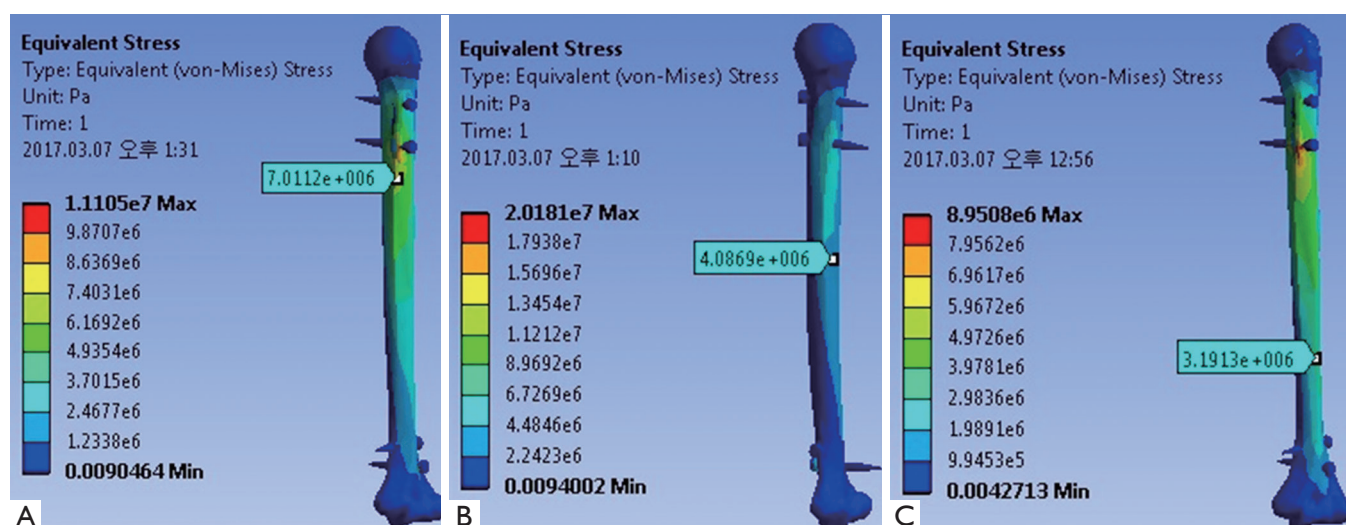


Figure 10 Stiffness of retrograde nailing on axial compression. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

we purposed to analyze the biomechanical properties of antegrade and retrograde nailing under three types of loads (axial compression, AP bending and torsion) in diaphyseal fractures according to the levels of the humerus.

In our study we formed 3D geometrical and FEM models of the humeral fractures and intramedullary nails using Solidworks software and analyzed biomechanical properties of humeral nailing under 3 types of loads: AP bending, torsion and axial compression with ANSYS 15.0 program. To estimate and compare biomechanical stability of antegrade and retrograde nailing, were formed using

Solidworks software based on CT scans of the humerus and analyzed with ANSYS 15.0 program. Biomechanical analysis was performed under three types of loads: AP bending, torsion and axial compression.

During the bending test, values of fracture stiffness by antegrade nailing were lower than those by retrograde nailing in proximal, distal diaphysis and midshaft. The displacement of fracture site in the proximal diaphysis by antegrade approach was considerably lower than in retrograde nailing, while displacements in the midshaft and distal diaphysis were not different between the nailing

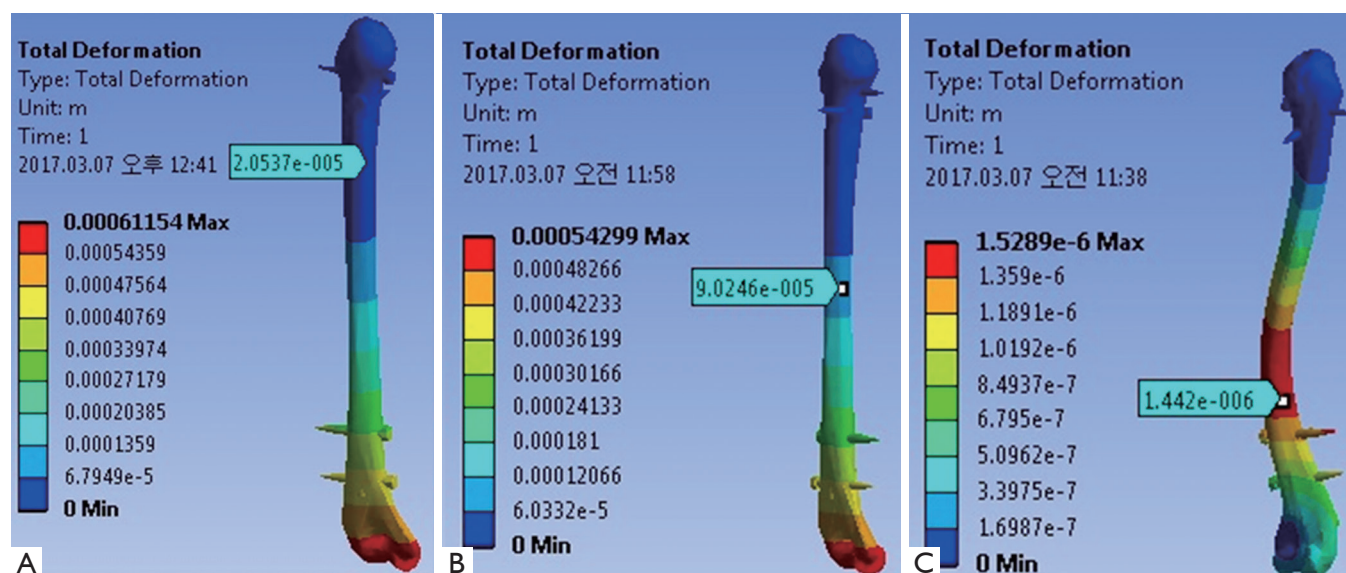


Figure 11 Displacement of antegrade nailing on axial compression. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

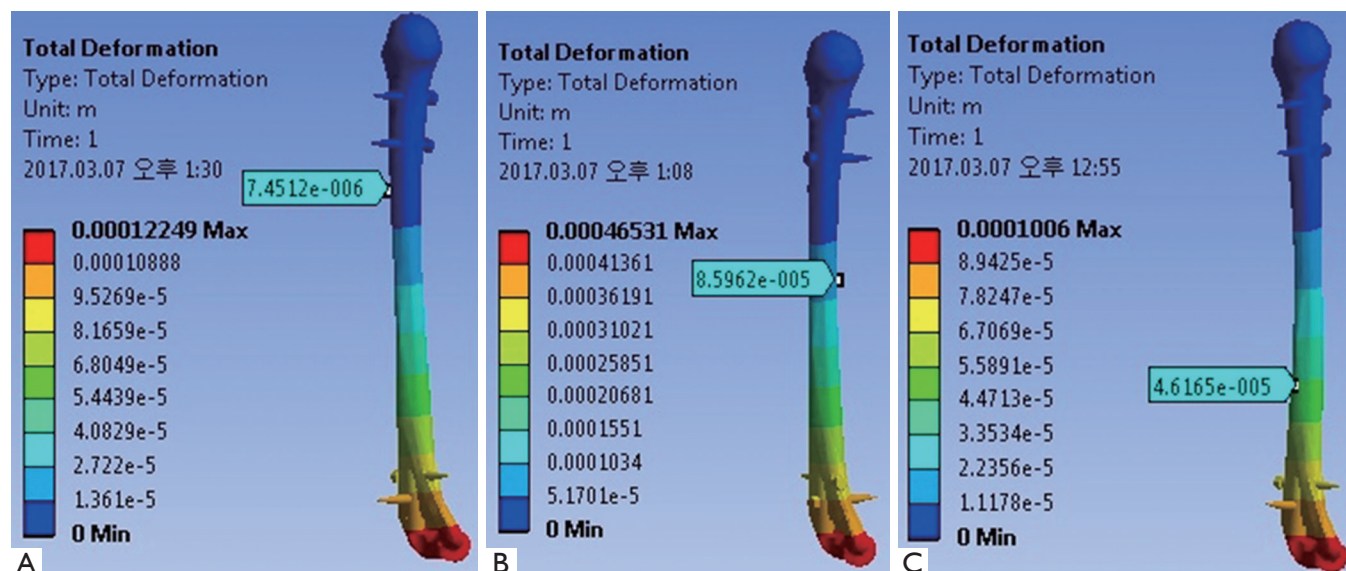


Figure 12 Displacement of retrograde nailing on axial compression. (A) Proximal diaphysis; (B) midshaft; (C) distal diaphysis.

directions. This means that antegrade nailing is safer than retrograde nailing on the bending force, especially in the proximal diaphysis.

Under torsional load, the values of fracture stiffness in antegrade nailing in the proximal, distal diaphysis and midshaft were somewhat greater than in retrograde technique, but the maximum values were not great on the contrary. Antegrade nailing resulted in less displacements

of fractures site in the proximal and distal diaphysis than retrograde nailing. On torsional load, antegrade nailing was found to be more stable than retrograde nailing in the proximal and distal diaphysis.

As applied axial compression, in the distal shaft, the value of fracture site stiffness by antegrade nailing was lower than the value by retrograde technique. Also, retrograde nailing showed less stiffness than antegrade nailing, but there was



Figure 13 Distal third fracture of the humerus operated with retrograde nailing. Radiographic controls after 24 weeks after the surgery show non-union with an angular deformation.

no significant difference between them. Displacements of fracture site and maximum displacements showed a similar tendency to the stiffness on axial compression. It is shown that under axial compression in the distal diaphysis, antegrade nailing is a safer procedure compared to retrograde approach.

Conclusions

Humeral nailing can be used by either antegrade or retrograde technique and its insertion direction may be dependent upon the preference of the surgeon. According to the levels of fracture in the humerus, however, antegrade and retrograde nailing produces different stabilities. In the proximal and distal diaphysis, antegrade nailing is a safer procedure than retrograde nailing biomechanically. There is no difference between antegrade and retrograde technique in the midshaft fracture.

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Footnote

Conflicts of Interest: All authors have completed the ICMJE uniform disclosure form (available at <http://dx.doi.org/10.21037/amj.2019.09.02>). The authors have no

conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. This article does not contain any studies with human participants or animals performed by any of the authors.

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