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Wave Plate; What is the Angle of Its Central Curved Segment Which Provides Biomechanically Optimal Stability for Femoral Shaft Fracture?: A 3-D Finite Analysis

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Abstract

Background: Even though intramedullary nailing of femoral shaft fracture is the standard surgical treatment as it is in tibial fracture, plate fixation might be a choice when the fracture involves open growth plate, patients are of shorter stature or have narrow canals. In these cases, fixation techniques with plate and screws, for example, percutaneous procedures involving wave plate, are useful thanks to minimal invasion and preservation of biological environment surrounding the fractures. However, this shape results in restricted weight bearing for postoperative 2 to 3 months and no availability to poor soft-tissue situation due to prominence. The purpose of the present study was to recommend optimal angle of central curved segment of wave plate when sustained fixation of femoral shaft fractures with wave plating by comparing biomechanical stability provided by fixations of wave plates with different angles of central curved segment. Method: Based on CT scans of the femur of human and wave plate, 3D-finite element models of femoral shaft fractures stabilized by wave plating were built to be analyzed for their biomechanical characteristics with ANSYS WORKBENCH programme when applied 3 types of loads including axial compression, antero-posterior bending and torsion. Results: The wave plate with 15° of central curved segment presented minimum stiffness of 122.0MPa, 52.2MPa, and displacements of 4.0mm, 2.0mm compared with those measured in fixations by wave plates with 10°, 20° and 25° of central curved segments under axial compression and antero-posterior bending. Torsion loads, however, produced stiffness which increase and displacements which decrease according to increase of the angles. Conclusion: It is biomechanically the most stable to choose a wave plate with 15° of central curved segment, when treated femoral shaft fractures with wave plating.

Keywords: Wave, plate, fracture, stiffness, deformity

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INTRODUCTION

To achieve bone healing in cases in which operative treatment is suitable after fractures, skeletal fixation providing absolute or relative stability is required as well as preservation of the blood supply to soft tissues and bone. Surgical fixation with absolute stability provides a mechanically neutral environment for fracture healing with no motion at the fracture site, while reducing the mechanical stimulus for repair. It results in primary bone healing without callus formation. In contrast, fixation with relative stability allows limited motion at the fracture site under functional loads leading to fracture repair with visible callus. For these reasons, techniques of

absolute stability are mainly applied to intraarticular fractures or some simple diaphyseal fractures which require anatomical reconstruction and early mobilization. In most of diaphyseal fractures, restoration of correct length, alignment and rotation is the treatment goals, and intramedullary nailing, plating and external fixation in modes of relative stability are usually used for bone healing [1, 2].

Though intramedullary nailing is the gold standard for the operative treatment of femoral and tibial diaphyseal fractures, plate and screw fixations might be used for young patients with open growth plate, patients who are of shorter stature or have narrow canals, and diaphyseal fractures extending proximally or distally [3–8]. In femoral diaphyseal fractures, plate fixation might be used for simple fractures by technique of absolute stability or multifragmentary fractures with technique of relative stability. In the late 1980s, Mast et al introduced a concept called "biological osteosynthesis" of not touching the fracture site for multifragmentary metaphyseal fractures when plating by using indirect techniques. Krettek et al first published on the percutaneous submuscular fixed angle plate insertion through a small skin incision and thereafter minimally invasive plate osteosynthesis (MIPO) technique has been popularized with evolution of locking plates over the world [9–11].

Meanwhile osteosynthesis using wave plate, which has a central curved segment so that it stands away from the bone at the affected area and allows autogenous bone grafts on the lateral cortex to share the axial loads with the plate more effectively, has been emerged by some authors [12–14]. The wave plate is beneficial to bridge plating of multifragmentary fractures or even nonunion thanks to its unique shape. However, this shape results in restricted weight bearing for postoperative 2 to 3 months and no availability to poor soft-tissue situation due to prominence. The purpose of the present study was to recommend optimal angle of central curved segment of wave plate when sustained fixation of femoral shaft fractures with wave plating by comparing biomechanical stability provided by fixations of wave plates with different angles of central curved segment.

METHOD

On the basis of the geometrical configurations of wave plates with 10°, 15°, 20° and 25° angles of central curved segments, locking head screws (Myohyangsan, Pyongyang, DPR Korea) and CT scans of the femur, 3D geometrical and finite element method (FEM) models of femoral shaft fracture (Arbeitsgemeinschaft fur Osteosynthesefragen/Orthopaedic Trauma Association (AO/OTA) classification type 32-A3) fixed with wave plates have been formed with Solidworks 2012 software. Using ANSYS WORKBENCH 15.0 programme, the models were meshed into 40,461 pieces of parabolic tetrahedron elements to compare biomechanical characteristics. By combining these models, wave plating models of the femoral shaft fracture were built, which consisted of the femur, wave plate and screws.

The mechanical values which were inputted to these FEM models are shown in Tables 1 and 2. To conduct finite element analysis, it was supposed that fixation by a wave plate and 4 screws in each fragment was undergone in femoral shaft fracture of a 42-year-old man, who was 1.71m tall and 60kg weighted. While the proximal end of the femur was being constrained, 600N of axial compression was transmitted, antero-posterior bending force was applied by 100N, and 5Nm of torsional moment through the distal femur. According to the fixations of wave plates with 10°, 15°, 20° and 25° angles of central curved segments, values of stiffness and displacement at the plate with screws and the femur have been obtained (Figure 1).

Table 1. Constants of bone used for FEM.

Bone	Elasticity coefficient (GPa)		Poisson ratio		Density(kg/m^3)
Cortical bone	E_1	11.5	ν_1	0.31	1960
	E_2	17.0	ν_2	0.46	
Cortical bone	4.50		0.12		400

Table 2. Constants of plate and screws used for FEM.

Materals	Elasticity coefficient (GPa)	Poisson ratio	Elasticity limit (MPa)	Strength limit (MPa)	Density (kg/m^3)
Plate (Stainless steel)	210	0.3	207	515	7800
Screw (Stainless steel)	210	0.3	200	506	7800

Figure 1. Angle of central curved segment of wave plate

RESULTS

Stiffness

Under both loads including axial compression and antero-posterior bending, the maximum values of stiffness when stabilized by the wave plate with 15° of central curved segment (Figure 2, 3) were the lowest compared with stiffness of fixations with wave plates with 10° (Figures 4, 5), 20° (Figure 6, 7 and 25° (Figure 8, 9) of central curved segments as shown in Table 3.

Torsion loads, however, produced a tendency to show that maximum values of stiffness which increase according to increase of the angles of the central curved segments (Figure 10, 11, 12, 13).

DISPLACEMENT

The displacements at the fracture sites under axial compression was the lowest when stabilized by the wave plate with 15° of central curved segment. In Table 3, the maximum displacements during axial compression tests and displacements at the fracture sites under torsion loads showed the different changes according to increase of the angles of the central curved segments of wave plates. With increase of the angles of the central curved segments of wave plates, the maximum displacements increased under axial compression (Figure 14, 15, 16, 17), in contrast, displacements at the fracture sites decreased during the torsion load tests (Figure 18, 19, 20, 21). However, the maximum displacements had no difference between the angles of central curved segments of wave plates when applied bending forces (Figures 22, 23, 24, 25).

DISCUSSION

By a prospective epidemiological study, femoral shaft fractures develop in 10-37 persons per 100,000 populations per year in a mixed urban/rural region. Intramedullary nailing results in high union rates leading to low complication rates, however, plate fixations have their unique indications and are still used in treatment of femoral shaft fractures [5–8, 15].

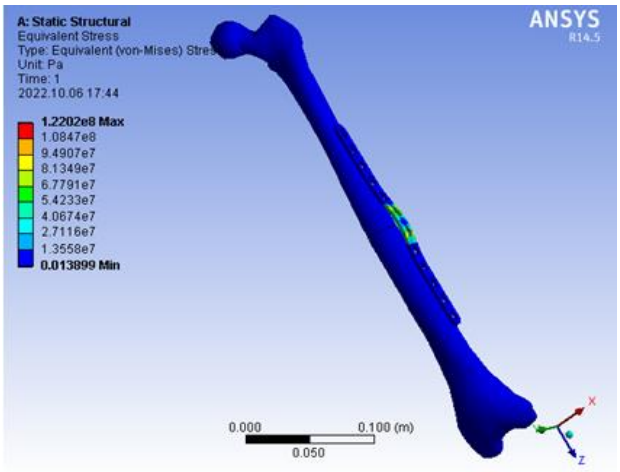

Figure 2. Stiffness of fixation by the wave plate with 15° of central curved segment on axial compression.

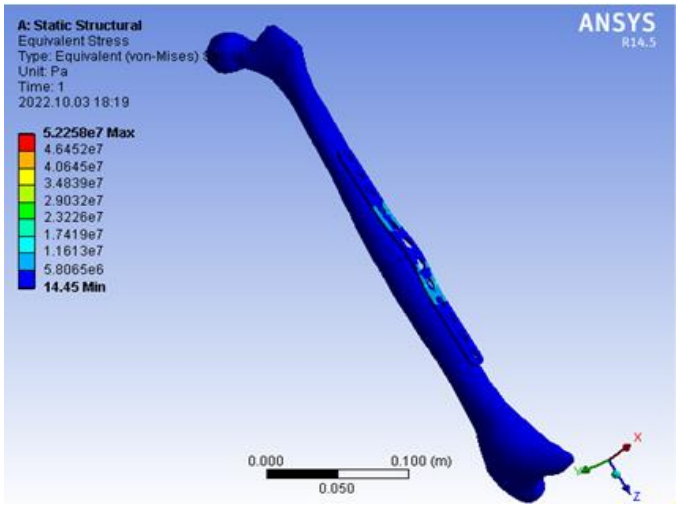

Figure 3. Stiffness of fixation by the wave plate with 15° of central curved segment under bending force.

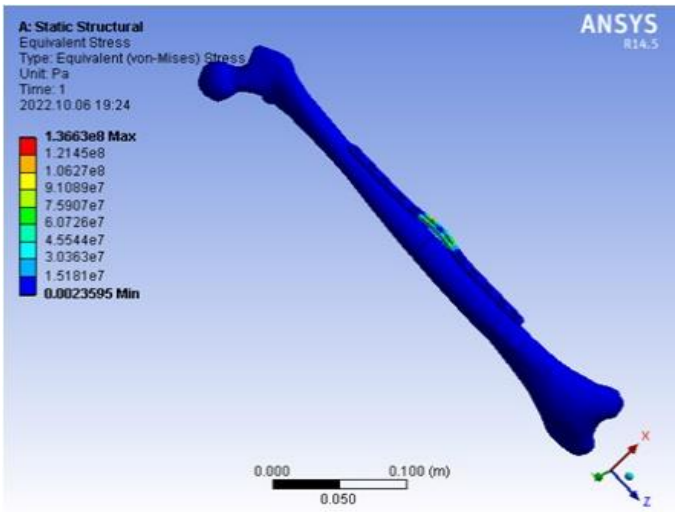

Figure 4. Stiffness of fixation by the wave plate with 10° of central curved segment on axial compression.

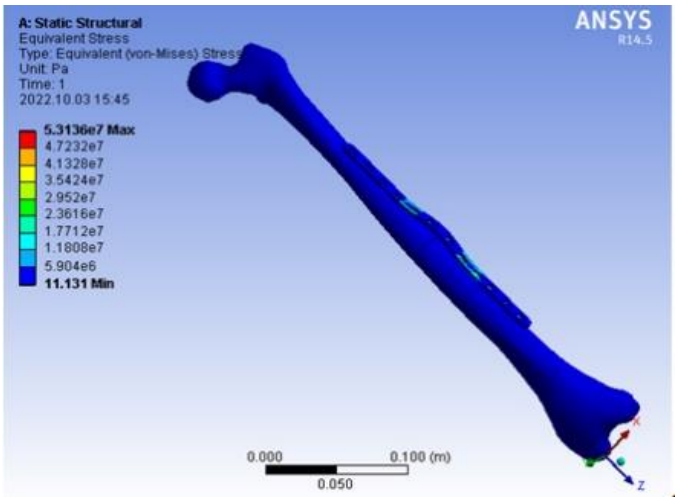

Figure 5. Stiffness of fixation by the wave plate with 10° of central curved segment under bending force.

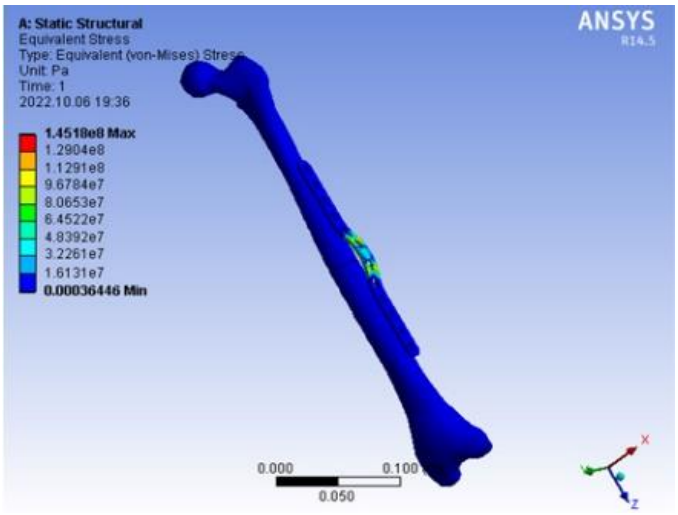

Figure 6. Stiffness of fixation by the wave plate with 20° of central curved segment on axial compression.

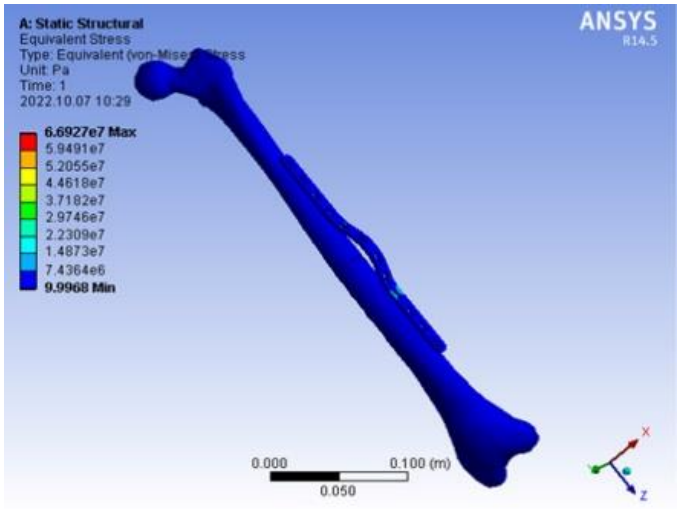

Figure 7. Stiffness of fixation by the wave plate with 20° of central curved segment under bending force.

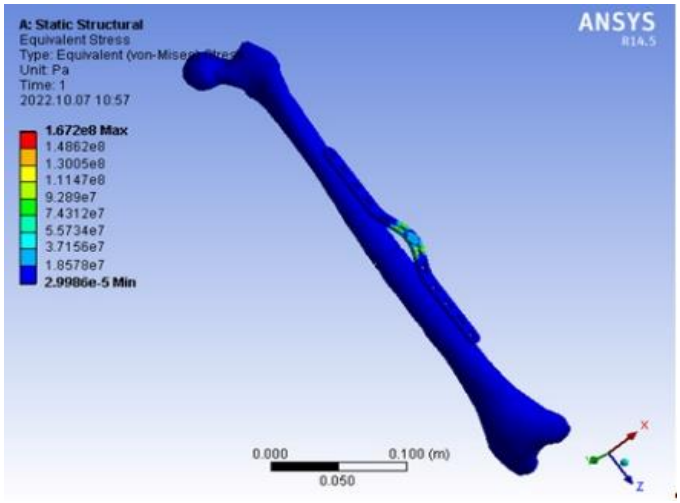

Figure 8. Stiffness of fixation by the wave plate with 25° of central curved segment on axial compression.

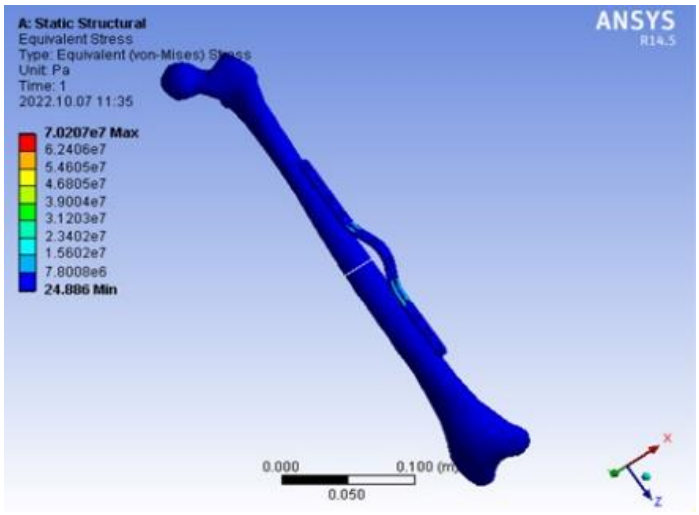

Figure 9. Stiffness of fixation by the wave plate with 25° of central curved segment under bending force.

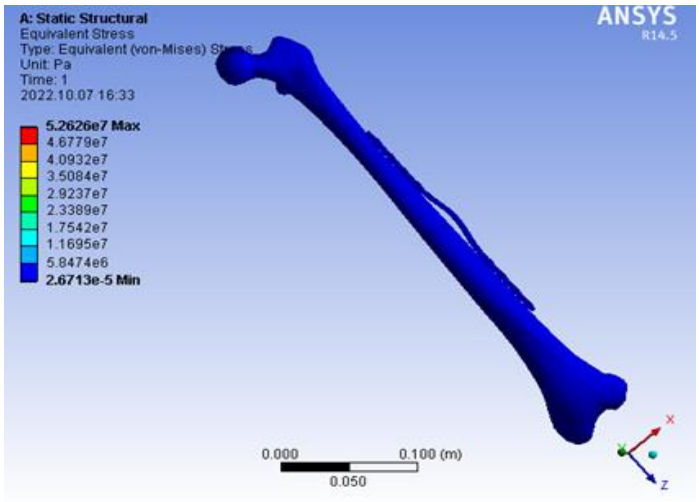

Figure 10. Stiffness of fixation by the wave plate with 10° of central curved segment during torsional load.

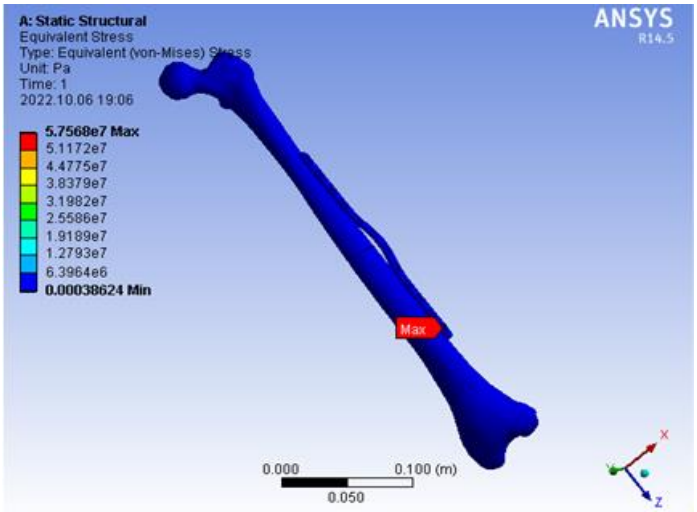

Figure 11. Stiffness of fixation by the wave plate with 15° of central curved segment during torsional load.

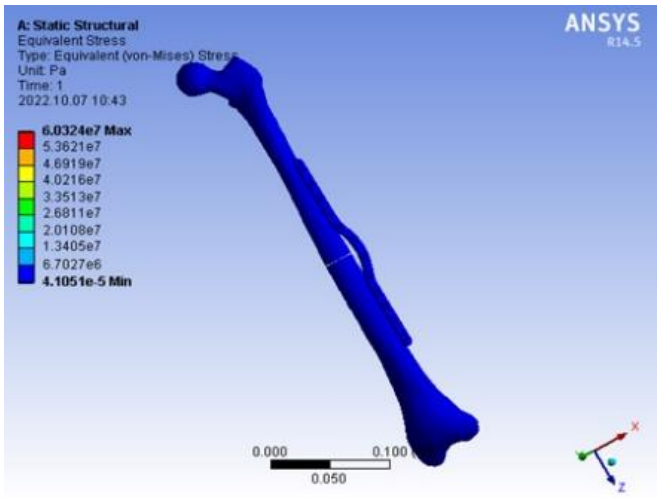

Figure 12. Stiffness of fixation by the wave plate with 20° of central curved segment during torsional load.

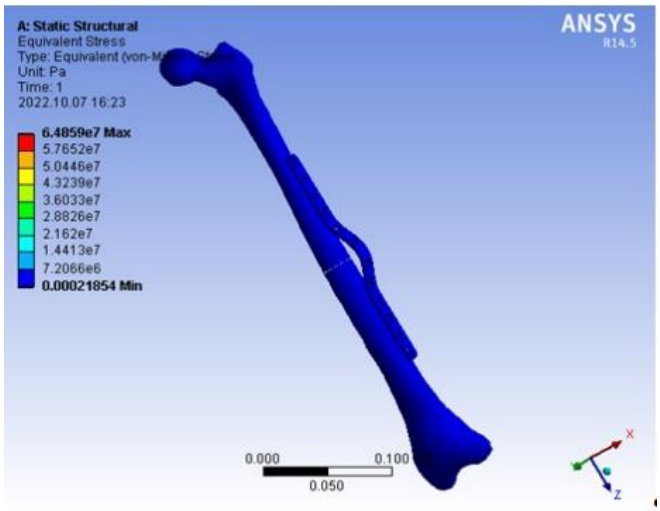

Figure 13. Stiffness of fixation by the wave plate with 25° of central curved segment during torsional load.

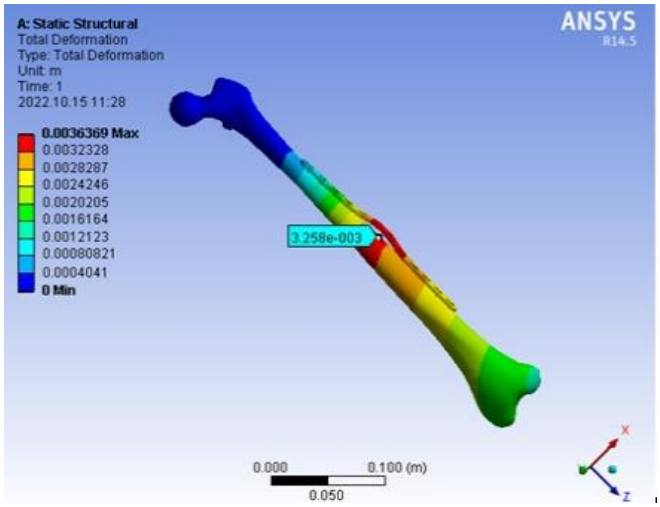

Figure 14. Displacement of fixation by the wave plate with 10° of central curved segment on axial compression.

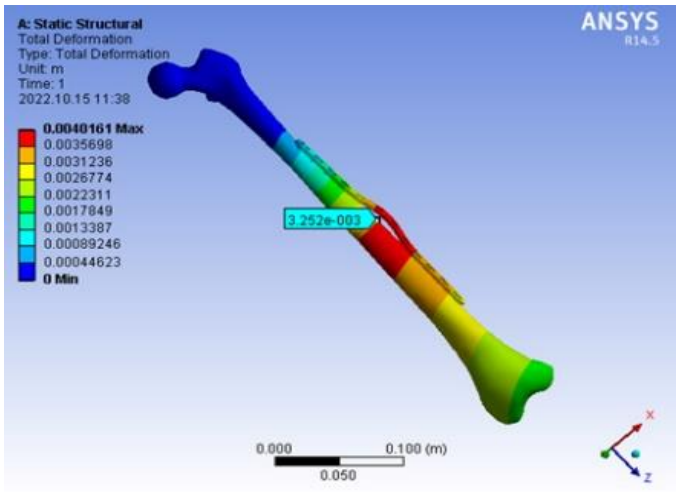

Figure 15. Displacement of fixation by the wave plate with 15° of central curved segment on axial compression.

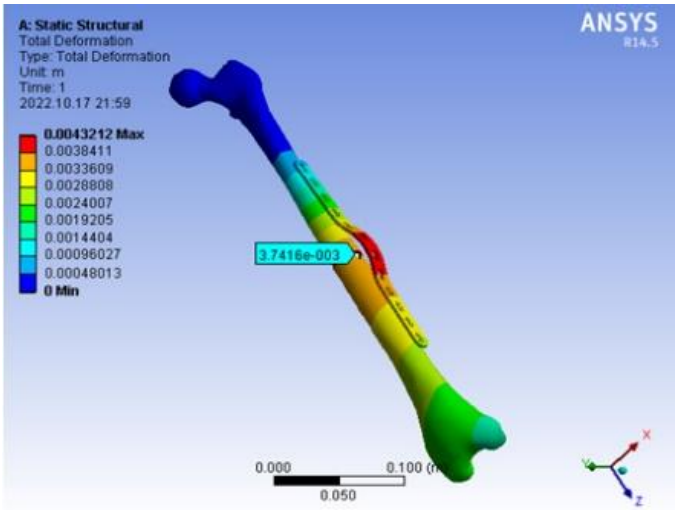

Figure 16. Displacement of fixation by the wave plate with 20° of central curved segment on axial compression

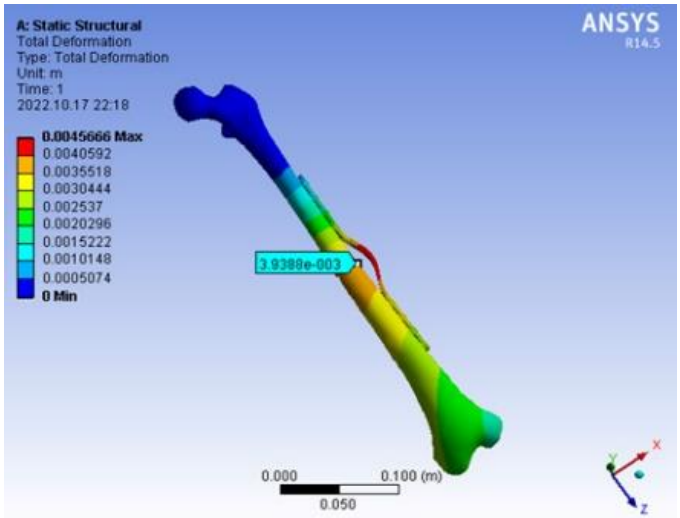

Figure 17. Displacement of fixation by the wave plate with 25° of central curved segment on axial compression.

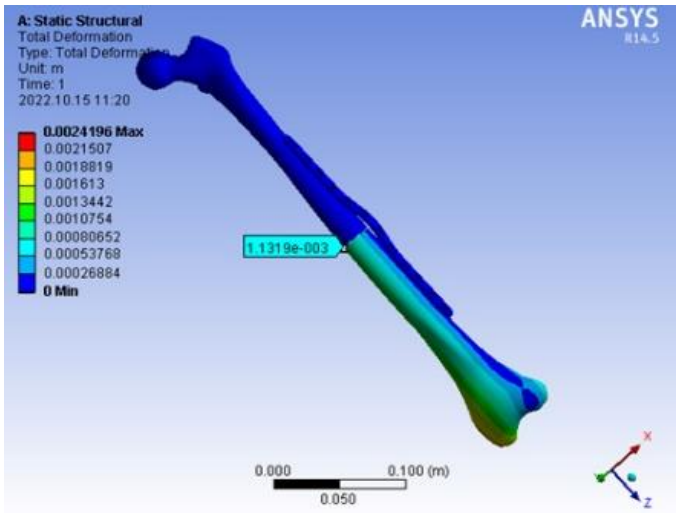

Figure 18. Displacement of fixation by the wave plate with 10° of central curved segment during torsional load.

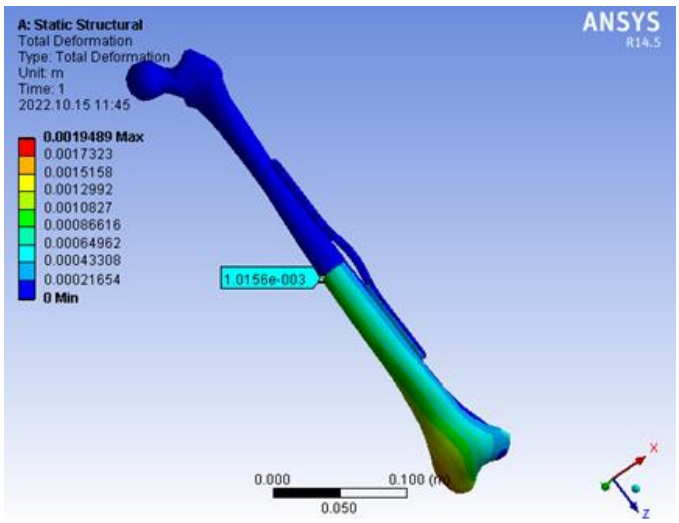

Figure 19. Displacement of fixation by the wave plate with 15° of central curved segment during torsional load.

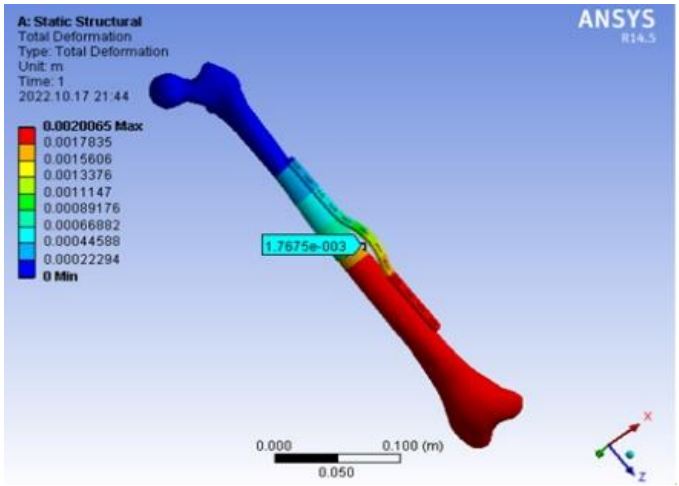

Figure 20. Displacement of fixation by the wave plate with 20° of central curved segment during torsional load.

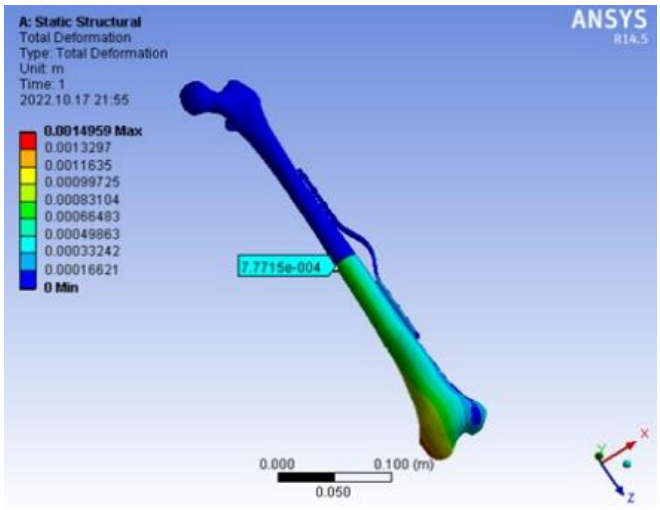

Figure 21. Displacement of fixation by the wave plate with 25° of central curved segment during torsional load.

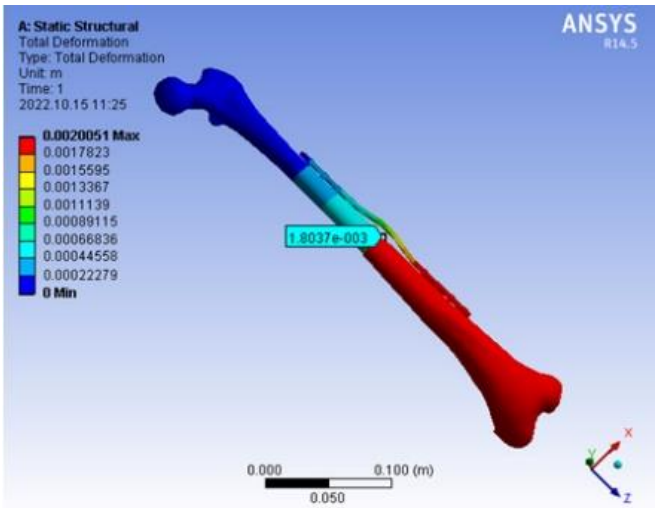

Figure 22. Displacement of fixation by the wave plate with 10° of central curved segment under bending force.

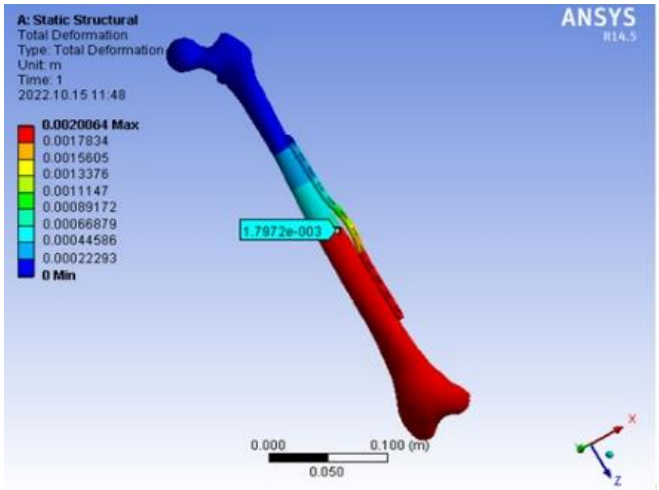

Figure 23. Displacement of fixation by the wave plate with 15° of central curved segment under bending force.

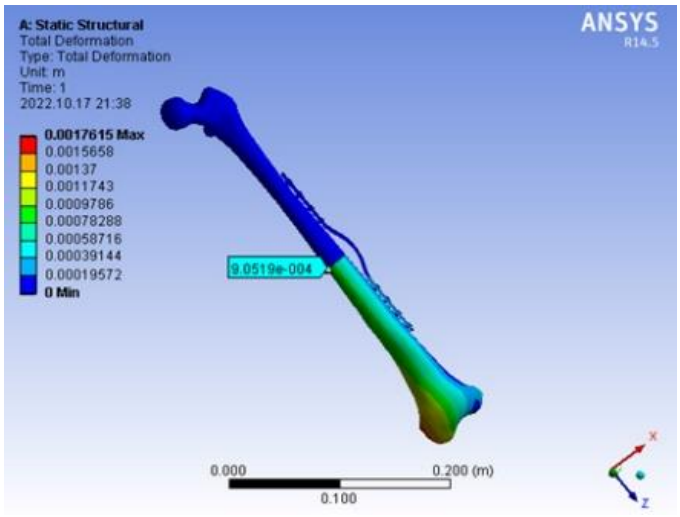

Figure 24. Displacement of fixation by the wave plate with 20° of central curved segment under bending force.

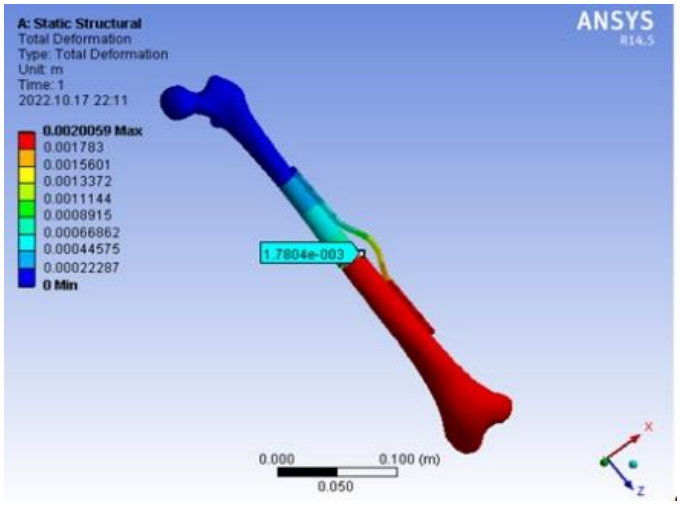

Figure 25. Displacement of fixation by the wave plate with 25° of central curved segment under bending force.

Table 3. Values of stiffness and displacements at the plate with screws and the femur according to angles of central curved segments of wave plates.

Angles of central curved segments of wave plates and external forces		Maximum stiffness [MPa]	Minimum displacements[mm]	Displacements at the fracture site[mm]
10°	Axial compresssion	136.6	3.6	3.26
	Bending	53.1	2.0	1.80
	Torsion	52.6	2.4	1.13
15°	Axial compresssion	122.0	4.0	3.25
	Bending	52.2	2.0	1.79
	Torsion	57.6	1.95	1.01
20°	Axial compresssion	145.2	4.3	3.74
	Bending	66.9	2.0	1.70
	Torsion	60.3	1.76	0.91
25°	Axial compresssion	167.2	4.56	3.94
	Bending	72.2	2.0	1.78
	Torsion	64.8	1.43	0.78

Figure 26. The wave plate with 15° of central curved segment.

Wave plating we studied mainly has been applied to femoral diaphyseal fractures and nonunions facilitating bone grafting. However, the shape of the plate with central curved segment which is prominent makes it not possible to apply to bones with poor surrounding soft tissue situations. In general, contouring of the plate with locking head screw holes may lead to prevent purchase of the screws and subcutaneous plates must be carefully contoured prior to insertion so they do not cause pressure necrosis of the wound [4]. In addition, wave plates are usually used for diaphyseal multifragmentary fractures by bridge plating, a fixation of relative stability, and the fracture site can play as a fulcrum around which the plate bends under combined compressive and bending loads.

Then plate stresses are significantly increased at the fracture site and therefore the plate should be long or be contoured properly to reduce the strains in the plate [16–19]. From these reasons, we conducted a study to determine the angle of its central curved segment of wave plates which provides biomechanically optimal stability for femoral shaft fracture.

In our study, we selected a AO/OTA classification type 32-A3 fracture stabilized with a wave plate with 10°, 15°, 20° or 25° angle of central curved segment and compared biomechanical measurements according to different angles of the central curved segments under the 3 types of loads above mentioned. The present study reveals that the wave plate with 15°of central curved segment provides the greatest stability in femoral shaft fracture. However, it is important to pay attentions to avoid torsional loads during the postoperative period, because fixation by the wave plate with 15°of central curved segment is not stable compared to fixations of wave plates with other angles of central curved segments when applied torsional loads. Angelini et al. compared wave plating with intramedullary nailing for simple femoral shaft fractures and concluded that wave plating represents a safe and efficacious treatment modality with high union and low complication rates serving as a cheaper treatment alternative than intramedullary nails [20]. Ring et al. reported wave plating with bone grafting has also been used successfully to obtain union in patients with infected nonunion of femoral shaft [21]. We also believe that wave plating is useful for femoral diaphyseal fractures, in particular, wave plate with 15°of central curved segment can lead to favorable outcomes by reliable stability (Figure 26).

This study has several shortcomings. First, the study did not comprise surrounding soft tissue structures of the femur which influence the displacements and fixations of fracture fragments in relation to building of 3-D finite element models and thereby the results might be misinterpreted. Second, the analysis was conducted by a programme on computer based on the data we set, which might also lead to different results if they changed.

CONCLUSION

It is biomechanically the most stable to choose a wave plate with 15° of central curved segment, when treated femoral shaft fractures with wave plating. As mentioned above, however, the study results we obtained are based on the measurements by 3-D geometrical models on computer, therefore, we suggest referring to our study in relation to clinical application.

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