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Numerical Analysis on K-wire Placement and Bone Fixation

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Abstract

Fractures of the hand and/or forearm account for 1.5% of all emergency department visits, with children aged 5 to 14 years accounting for 26% of these fractures. Percutaneously inserted wires (K-wires) are frequently used in the treatment of hand bone fractures. K-wires are inexpensive, easily available, and easy to remove. The main disadvantage of using K-wires is that stabilization may not be as adequate as expected which is critical for fractured bone healing. Therefore, the research objective of the current study is to investigate the relationship between K-wire placement and bone fixation. The effect of three factors of K-wire placement on bone fixation have been studied. The three factors are the angle between K-wires, the distance between K-wires, and the distance between the cross point of K-wires and the fracture surface. 3D modeling and finite element analysis have been applied to study the effect on deformation of the fractured bones under constant tensile and torsional loading as it relates to the three geometric factors. Changing the parameters of the K-wire placement has relatively less effect on the tension-induced bone deformation than the torsion-induced bone deformation, especial for changing the parameter of vertical and horizontal distance, which suggests that rotational stability should be the main concern. Increasing the vertical and horizontal distances and the angle decreases the maximum deformation of bone under torsional loading greatly which indicates the better stability of the fractured bone during healing. The results would enable doctors to optimize patient outcomes and reduce unnecessary invasiveness.

Keywords: K-wire; Bone fracture; Finite element analysis

Introduction

Hand injuries represent approximately 15% of all trauma-related emergency service visits, with fractures present in 11.4% of those cases.[1] Metacarpal fractures are present in 25.9% of hand bone fractures, with specifically the fifth metacarpal bone being the most commonly fractured at 9.8% of visits. Without proper treatments, even a small fracture in the hand could lead to permanent functional loss.[2]

Common treatments for hand bone fractures include nonsurgical and surgical options. Nonsurgical treatments are relatively inexpensive and involve a closed reduction, where a doctor manipulates the bone fragments back into position; usually accompanied by three to six weeks in a cast to support the regrowth of the bone. However, such simple immobilization of a fracture might cause an unacceptably large degree of angulation and displacement of the fracture surfaces leading to decreased function of the hand after healing.[3] Surgical treatments involve the use of small metal devices such as plates or pins to keep the bone fragments in position, sometimes accompanied by a cast, and are for more severe injuries.[4] Among these surgical treatments, percutaneously inserted wires and screws have been widely adopted to this day.[3]

Developed by Martin Kirschner in 1927, percutaneous Kirschner wires (K-wires) are one of the most widely used treatments in current days[5], capable of treating most hand bone fractures.[3] For this method of bone fixation, straight, stiff wires are inserted through fractured bones to hold the fragments in place during healing, as shown in Figure 1.[6,7] The diameter of wires typically ranges from 1.0 to 2.0 mm depending on the size of the patient, typically with 2 cm left sticking out of the skin.[5] The use of K-wires is ideal for multifragmentary fractures and small bones, making them a common treatment for children. The wires are inserted either by hand or drill, typically using up to 3 wires for a simple fracture. K-wires are inexpensive, easily available, and easy to remove. However, in exchange for a simple way to potentially stabilize fractures, there are compromises and the stabilization may not be as adequate as expected. [7,8]

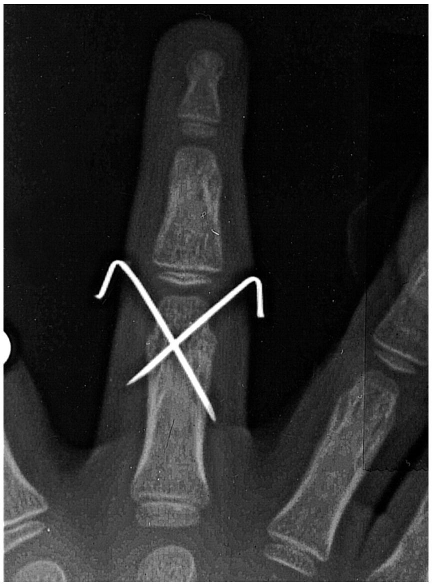


Figure 1: K -wire fixation[7]

K-wires are typically inserted through the free fragment into the main fragment, with a focus on maintaining distance between the wires as they cross the fracture line in order to increase rotational stability.[9] The distance and angle between the wires as well as the relative position of the cross point to the fracture line might affect the rigidity of the fixation of the fractured bones. To the best knowledge of authors, no systematic study has been conducted on the effect of these geometric factors on bone rigidity. Therefore, the objective of this research work is to investigate the relationship between K-wire geometric factors and rigidity of bone fixation through 3D modeling and finite element analysis. Through exploring the three factors, the procedure for placing the K-wires can be improved.

Methods

K-wire placement was modeled using Solidworks and then evaluated using finite element analysis, in which ANSYS software has been used. To replicate a small bone, each model includes an inner cylinder of trabecular bone, an outer layer of cortical bone, and a horizontal layer of bone with very low material properties (in order to simulate the fracture line). Figure 2 shows a labeled model of a hand bone.

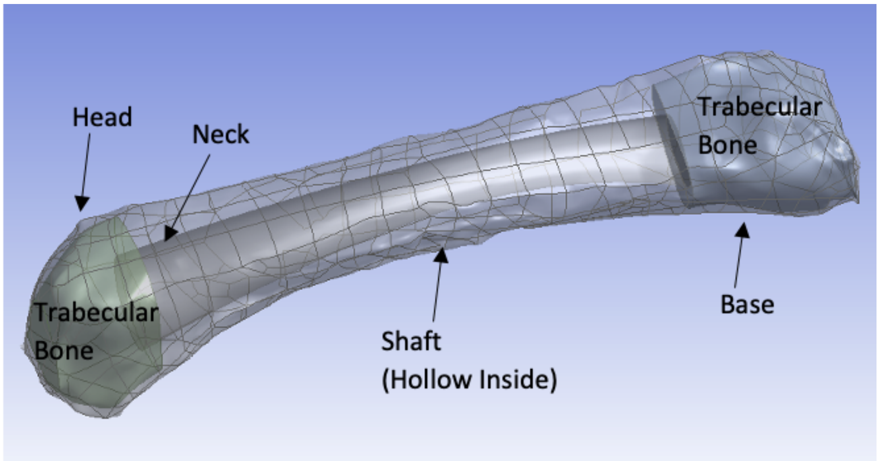


Figure 2: Example Model of Bone (no wires)

The geometry and material properties used to model the bone are similar to that of a fifth (pinky) metacarpal, but are intentionally simple so as to keep the scope of the study on the impacts of K-wire geometry. The K-wires were approximated as steel, but can be made of different materials such as titanium and Nitinol.[12] It is assumed that the wire is well bonded with the bone in the simulation. The material properties and dimensions of the bone and K-wire are listed in Table 1.[10,11] A small section of fractured bone, shown in Figure 3, is isolated for simulation purposes.

Table 1: Dimensions and Material Properties[10,11]

Property	**K-Wire (Steel)**	**Cortical Bone**	**Trabecular Bone**	**Fracture Layer**
Elastic Modulus (GPa)	200	17	0.35	0.00005
Poisson's Ratio	0.3	0.45	0.45	0.45
Outer Diameter (mm)	1	9	4.5	9
Thickness (mm)	N/A	3	3	1

For consistency, the fracture layer is horizontal with two K-wires placed in a cross formation. The geometric variables being evaluated are the vertical distance from the center of the fracture layer to the center of the cross point, the angle from the center of one K-wire to the other, and horizontal distance between the centers of the K-wires. Figures 4a-7 compare models in order to show these variables more clearly.

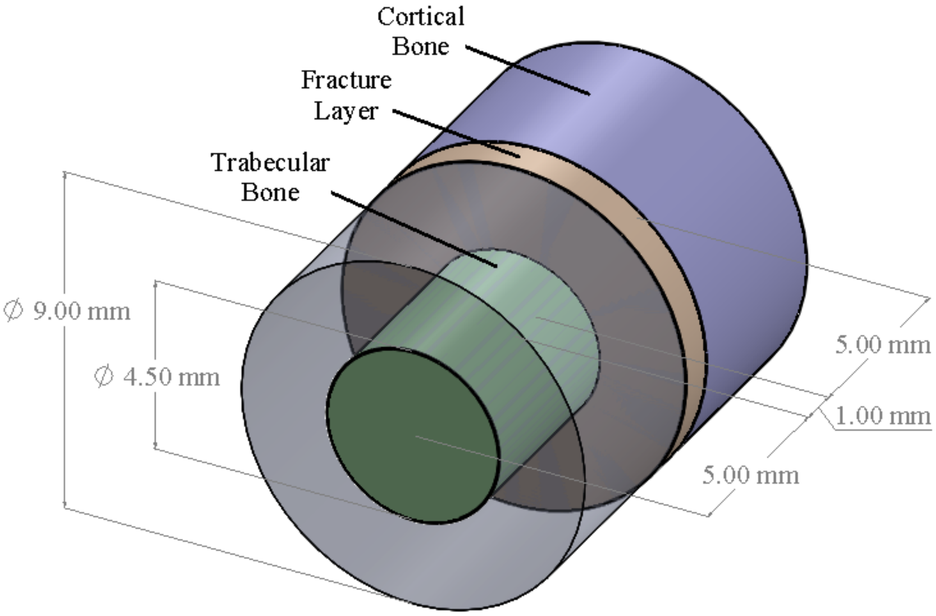
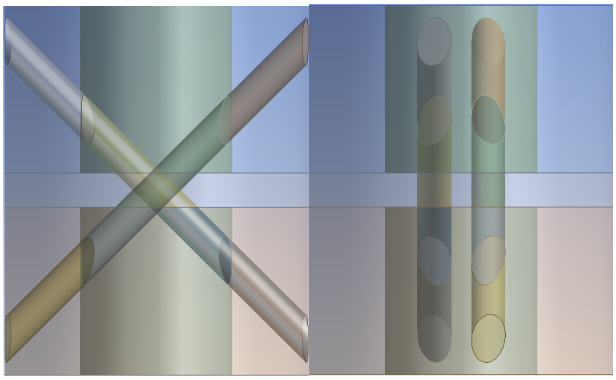


Figure 3: Labeled Bone with Dimensions (mm)

Finite Element Models and Analysis
The baseline model, shown in Figures 4a and 4b, simulates the bone when the cross point of the K-wires is coincident with the fracture layer. The angle between wires is 90^o and the gap between the centers of the two wires is 1.6 mm. Figures 5-7 show models which deviate from the baseline by one variable. Figure 5 shows an example of a 2 mm change in vertical distance between the fracture line and K-wire cross point. Figure 6 shows an example of a 30^o change in angle between the K-wires. Figure 8 shows an example of a 0.4 mm change in horizontal distance between K wires. The geometry of each model can be seen in Table 5 of Appendix A. The length of the model used to vary the angle had to be increased to ensure that the steeper angles did not result in K-wires which exited the top of the bone rather than the side. The bone on either side of the fracture layer was extended from 5 mm to 10 mm.



a. b.

Figure 4a: Baseline Front View
Figure 4b: Baseline Side View

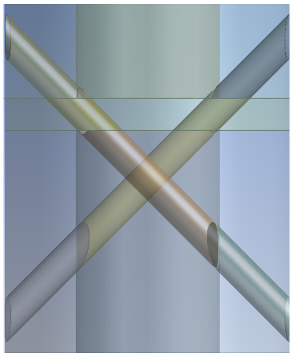


Figure 5: Vertical Change Front View

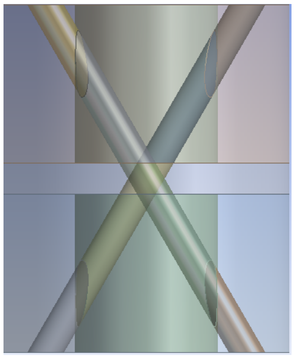


Figure 6: Angle Change Front View

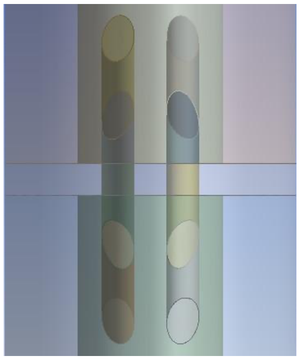


Figure 7: Horizontal Change Side View

Results and Discussions

Figure 8a shows the FEA results of the baseline model under a tension of 100 N, resulting in a maximum deformation of 0.0618 mm. Figure 8b shows the baseline model under a torsion of 1 N.m, resulting in a maximum deformation of 0.829 mm. The results of the example models (including the baseline) are shown in Table 6 and Figures in Appendix A.

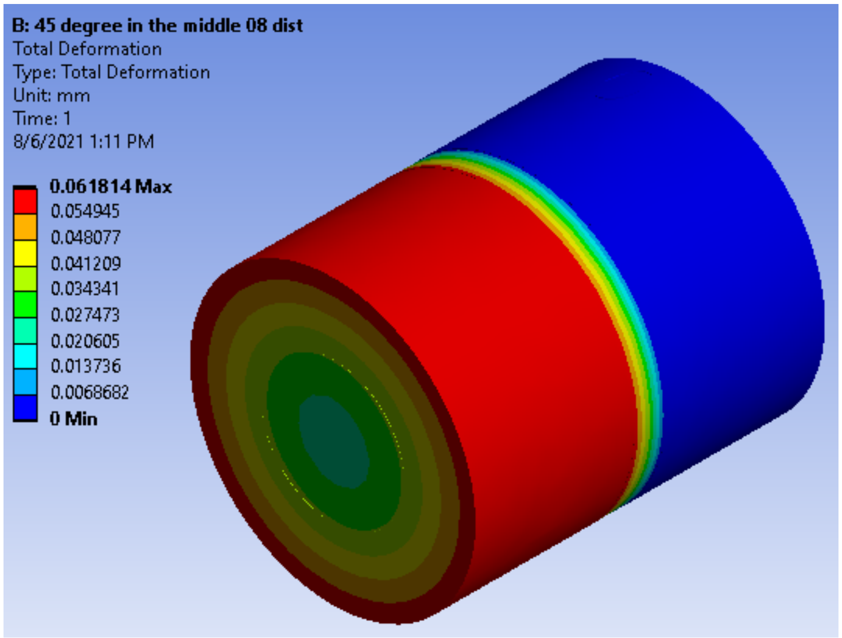


Figure 8a: Baseline Model Under Tension of 100N

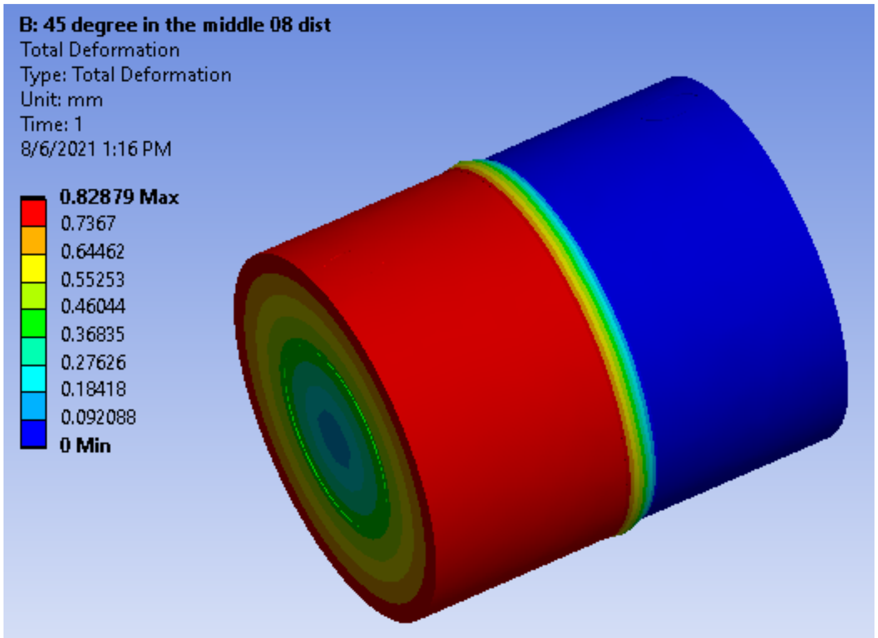


Figure 8b: Baseline Model Under Torsion of 1 N.m.

Figure 9 shows the relationship between bone deformation and the vertical distance between K-wires. Table 2 shows the data used to create Figure 9. The vertical distance ranged from 0.00 to 3.00 mm with seven data points at 0.50 mm apart. The torsion-induced deformation was much more drastically affected, with a range of 0.7409 mm compared to 0.0456 mm for tension-induced deformation, with the steepest decline occurring between 1.50 and 2.00 mm. The max deformation at 0mm distance is 2.8 times in tension and 9.7 times in torsion of 3mm distance.

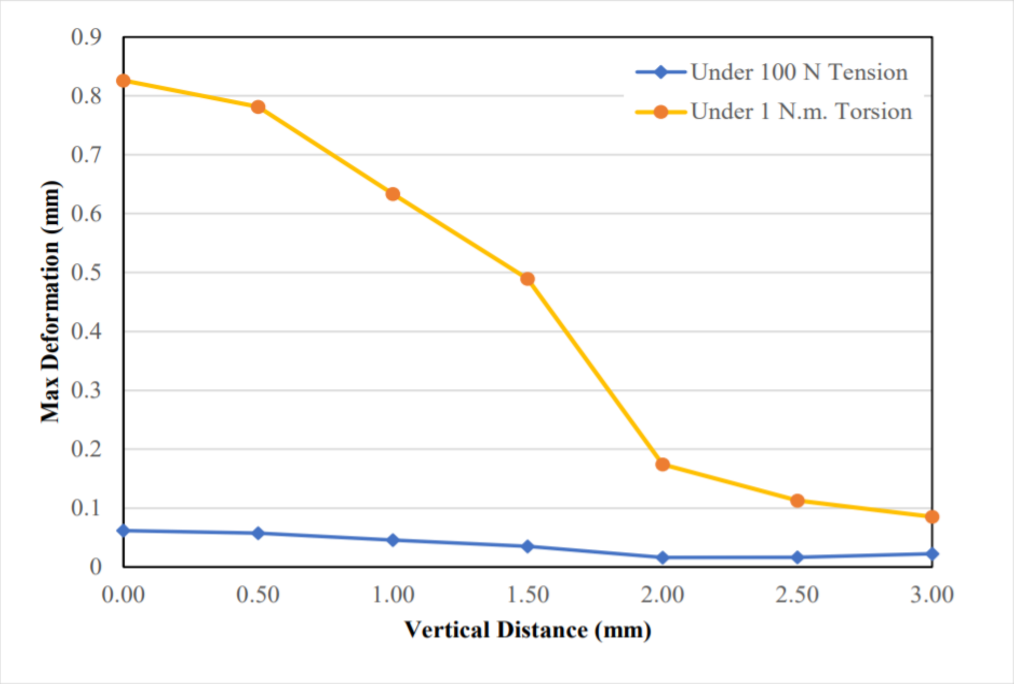


Figure 9: Vertical Distance Results

Table 2: Vertical Distance Data

Vertical Distance (mm)	0.00	0.50	1.00	1.50	2.00	2.50	3.00
Deformation Under 100 N Tension (mm)	0.0618	0.0577	0.0458	0.0350	0.162	0.0167	0.0221
Deformation Under 1 N.m. Torsion (mm)	0.8261	0.7812	0.6335	0.4895	0.1742	0.1126	0.0852

Figure 10 shows the relationship between bone deformation and the angle between K-wires. Table 3 shows the data used to create Figure 10. The angle ranged from 60° to 120° with seven data points at 10° apart. A larger angle resulted in a smaller torsion-induced deformation, with the steepest decline occurring between 60° and 70°. Increasing the angle resulted in an increased tension-induced deformation. As the angle changes from 60° to 120°, the maximum deformation increases 1.6 times in tension, but it drops 1.5 times in torsion.

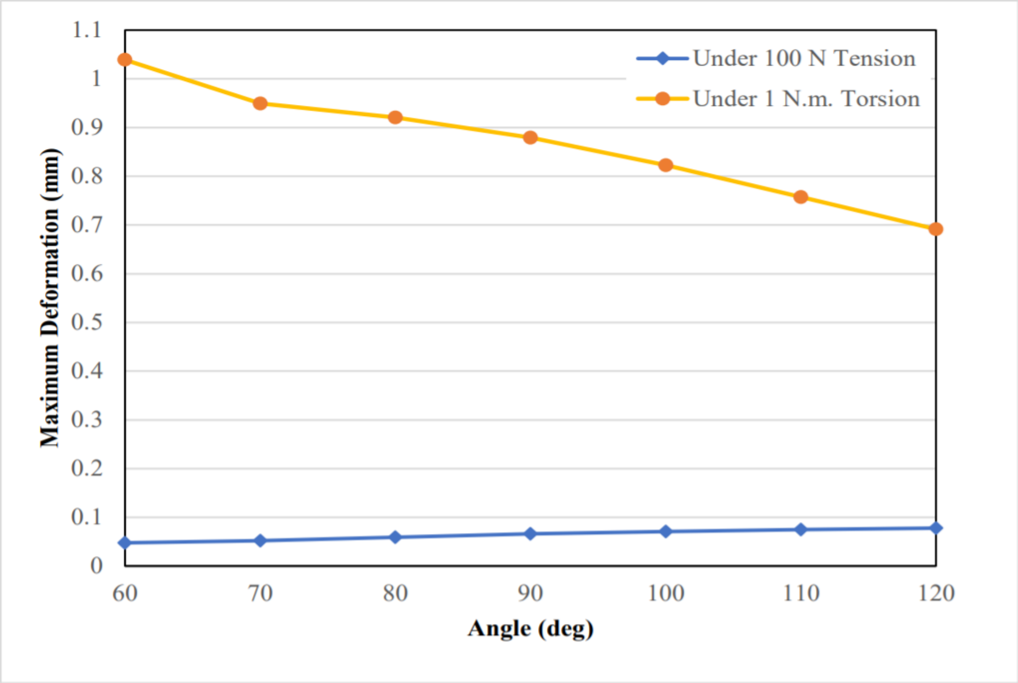


Figure 10: Angle Results

Table 3: Angle Data

Angle (deg)	60	70	80	90	100	110	120
Deformation Under 100 N Tension (mm)	0.0476	0.0524	0.0594	0.0661	0.0707	0.0750	0.0779
Deformation Under 1 N.m. Torsion (mm)	1.0392	0.9493	0.9207	0.8797	0.8228	0.7572	0.6915

Figure 11 shows the relationship between bone deformation and horizontal distance between K-wires. Table 4 shows the data used to create Figure 10. The distance ranged from 1.20 to 6.00 mm with seven data points at 0.80 mm apart. The torsion-induced deformation once again more drastically affected, with a range of 0.9212 mm compared to 0.0485 mm for the tension-induced deformation. A larger horizontal distance resulted in a smaller torsion-induced deformation, with the steepest decline occurring between 1.20 and 2.00 mm. The maximum deformation drops 4.4 times in tension, but 17.1 times in torsion.

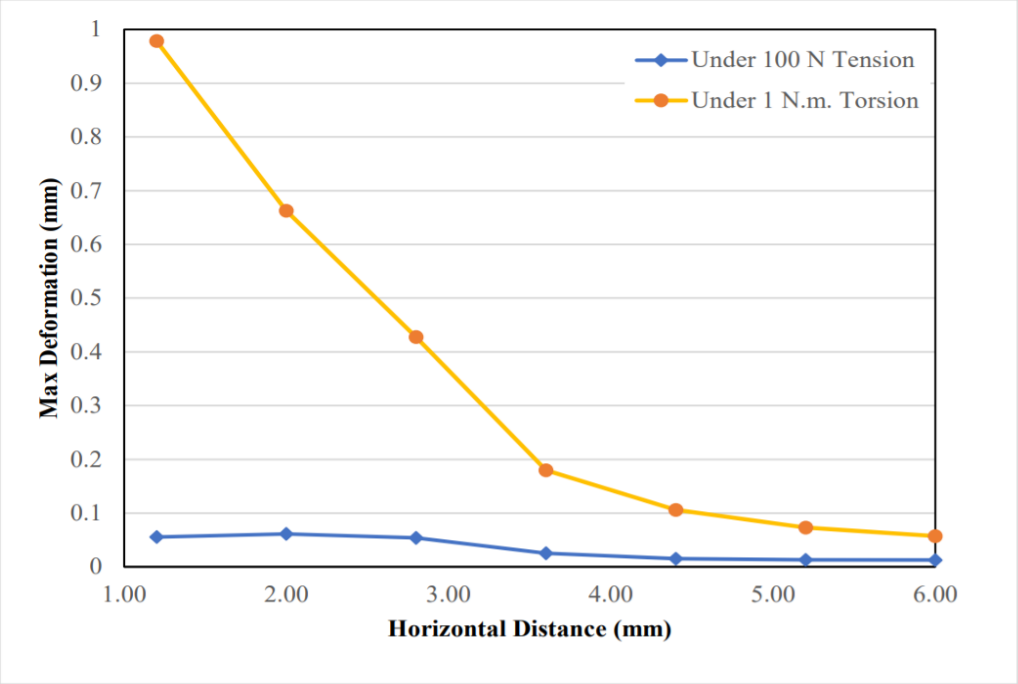


Figure 11: Horizontal Distance Results

Table 4: Horizontal Distance Data

Horizontal Distance (mm)	1.20	2.00	2.80	3.60	4.40	5.20	6.00
Deformation Under 100 N Tension (mm)	0.0557	0.0613	0.0541	0.0254	0.0152	0.0132	0.0127
Deformation Under 1 N.m. Torsion (mm)	0.9784	0.6628	0.4273	0.1800	0.1061	0.0731	0.0572

Conclusion

Three geometric factors of K-wire placement were evaluated as they varied from a common baseline: the vertical distance between the K-wire cross point and fracture line, the angle between K-wires, and the horizontal distance between K-wires. Two loading conditions, 100 N of tension and 1 N.m. of torsion, were simulated using finite element analysis and the resulting deformation was recorded. The goal of the experiment was to identify the relationship between

K-wire placement and bone deformation, where smaller deformations correlate with better bone stability and patient outcomes.

Changing the geometry parameters of the K-wire placement had relatively less effect on the tension-induced bone deformation than the torsion-induced bone deformation, especial for changing the parameter of vertical and horizontal distance, which suggests that translational security of the bone is not as sensitive to the parameters, while rotational stability should be the main concern. The relationships displayed in the data suggest that rotational stability of the bone would be higher when the K-wires are placed farther away from the fracture line, as well as with the highest horizontal distance from one another allowed by the bone diameter. A larger angle between the K-wires also appears to increase the rotational stability.

The ability to implement these relationships is limited by real-world constraints, such as the accuracy that can be reasonably expected from a doctor during placement. Replicating the study with baseline models that represent different types of fractures and/or K-wire placement would expand the scope of the results. This work sheds light on potential future clinical trial to improve the procedures.

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Appendix A - Example Finite Element Models and Analysis

Table 5 shows a summary of the models discussed in the "*Finite Element Models and Analysis*" section. "Vertical Distance" refers to the vertical distance between the center of the fracture layer and center of the K-wire cross point. "Angle" refers to the inner angle between the K-wires. "Horizontal Distance" refers to the horizontal distance between the center of each K-wire.

Table 5: Model Summaries

Model	**Vertical Distance (mm)**	**Angle (deg)**	**Horizontal Distance (mm)**
Baseline	0	90	1.6
Vertical Change	2	90	1.6
Angle Change	0	60	1.6
Horizontal Change	0	90	2

Table 6 summarizes the maximum deformation experienced by each model when under either a tension of 100N or torsion of 1 N.m.

Table 6: Example Models Maximum Deformations

Condition	**Maximum Deformation (mm)**			
	Baseline Model	Vert. Change Model	Angle Change Model	Horiz. Change Model
100 N Tension	0.0618	0.0162	0.0504	0.0605
1 N.m. Torsion	0.829	0.176	1.113	0.655

Figures 12a - 15b show the models under a tension of 100 N or torsion of 1 N.m.

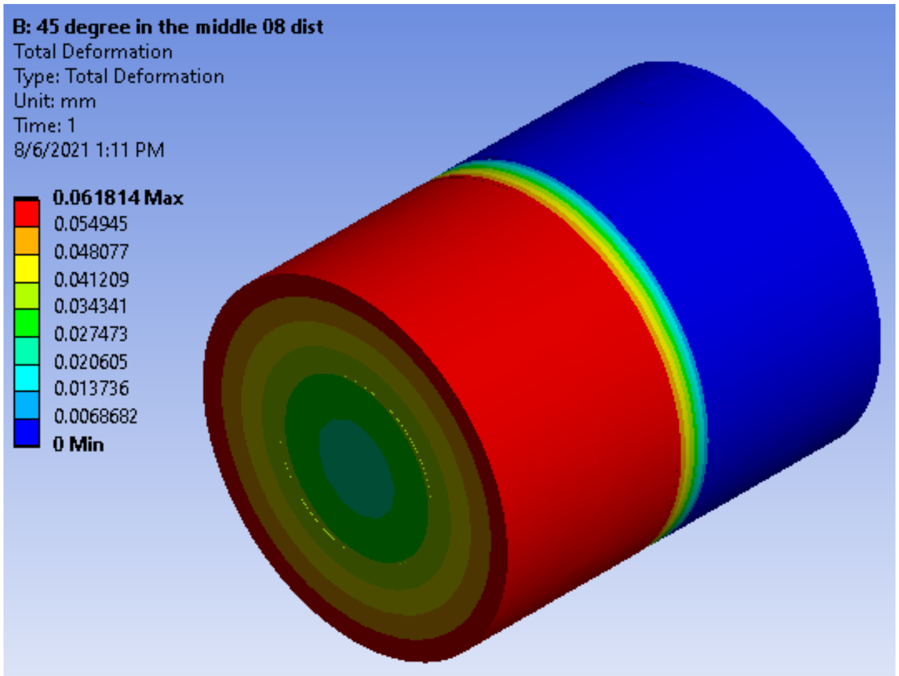

Figure 12a: Baseline Model Under Tension of 100N

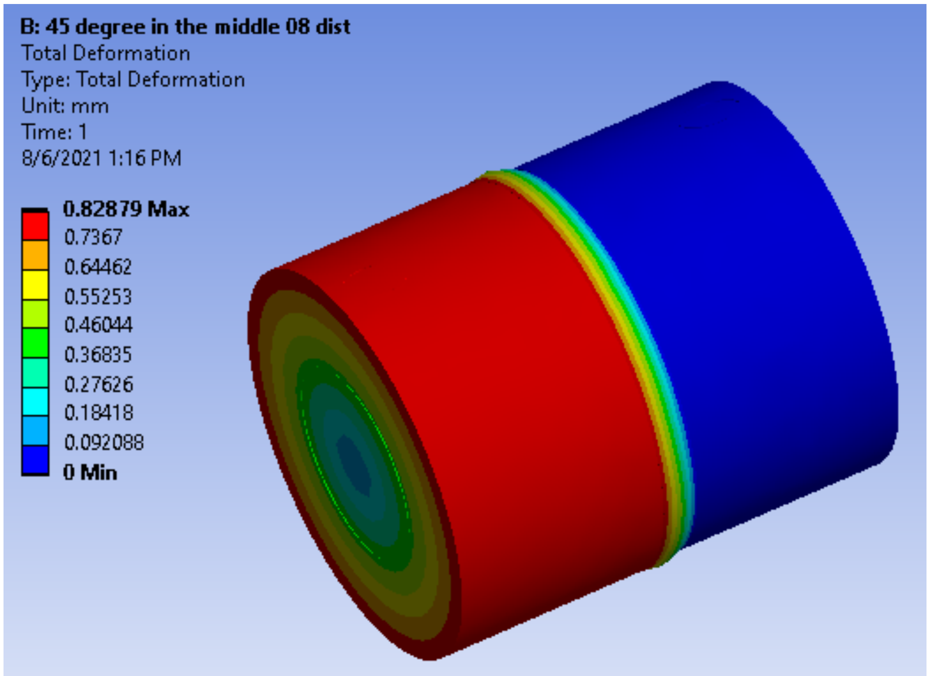

Figure 12b: Baseline Model Under Torsion of 1 N.m.

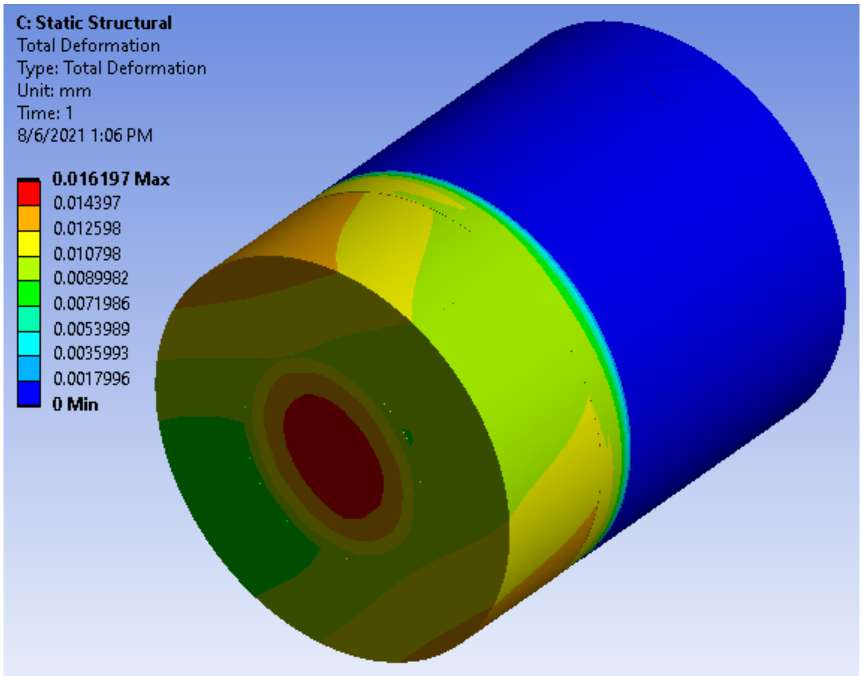

Figure 13a: Vertical Change Model Under Tension of 100N

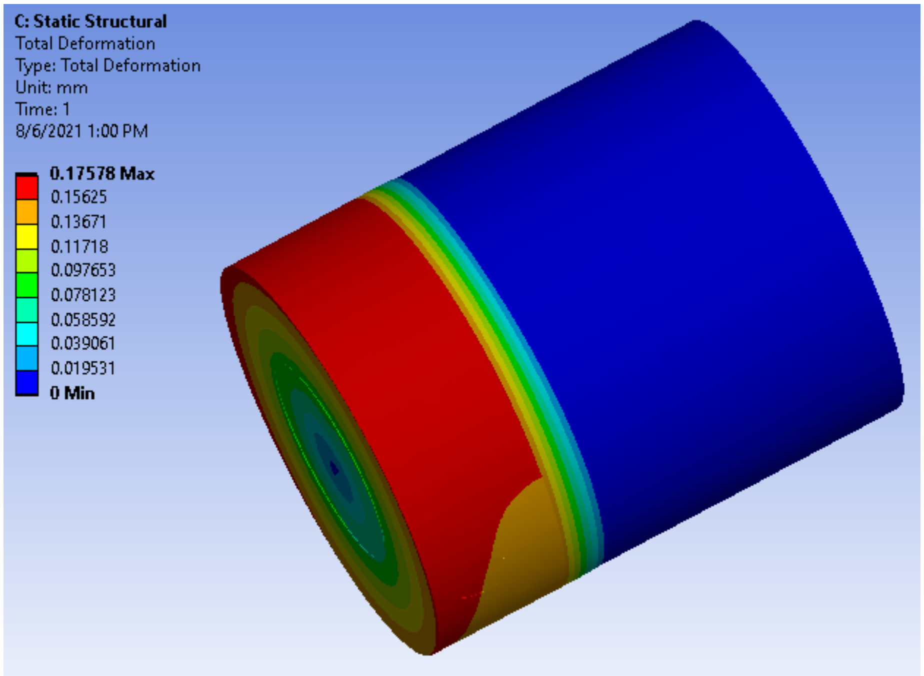

Figure 13b: Vertical Change Model Under Torsion of 1 N.m.

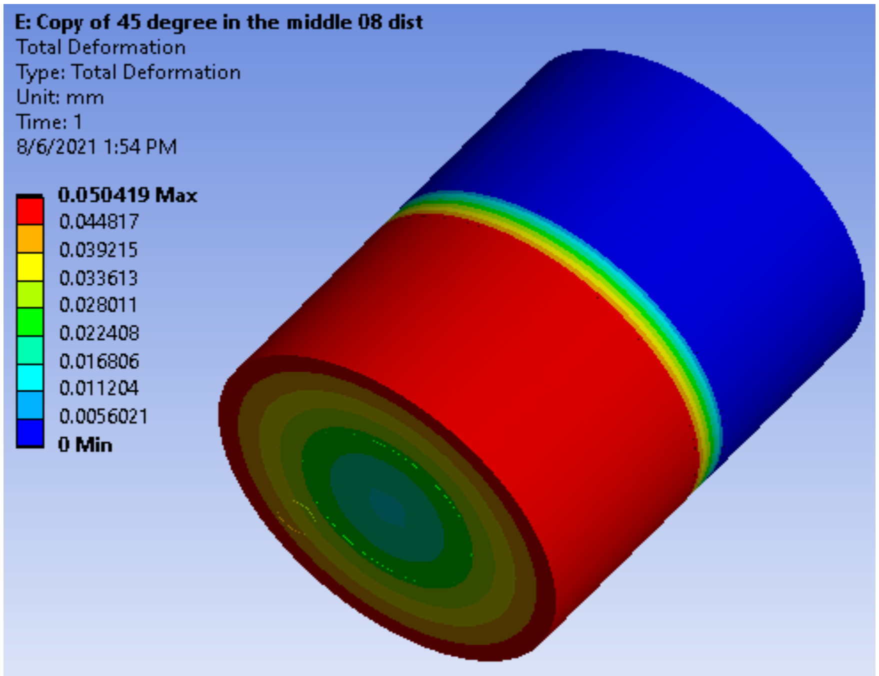

Figure 14a: Angle Change Model Under Tension of 100N

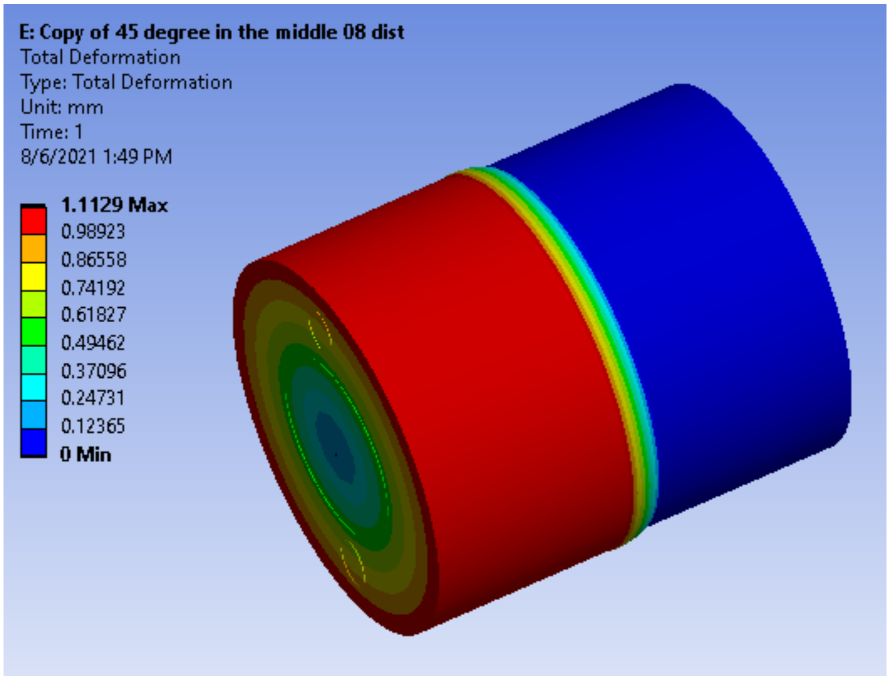

Figure 14b: Angle Change of Model Under Torsion of 1 N.m.

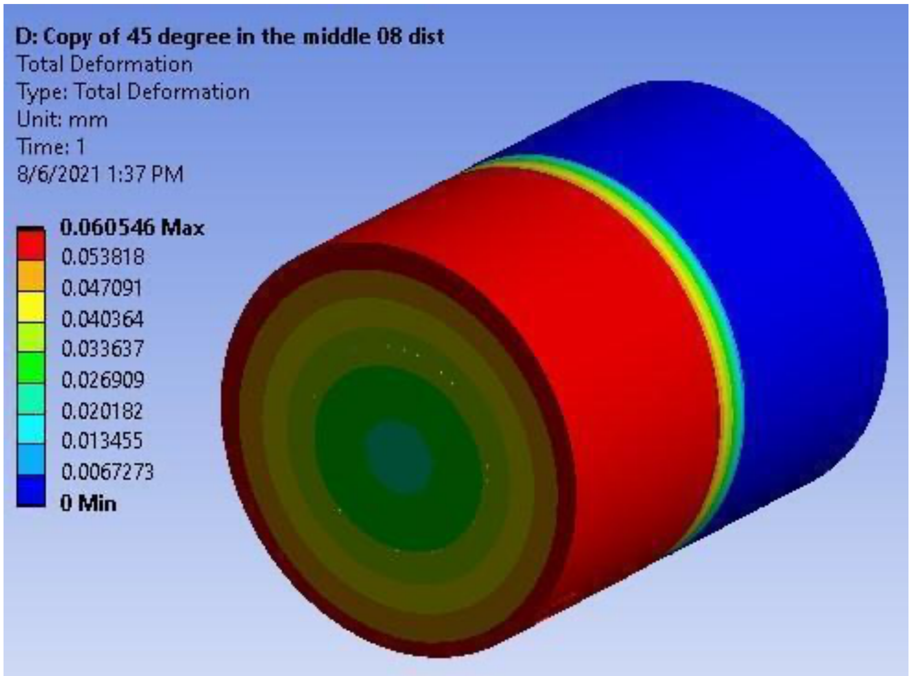

Figure 15a: Horizontal Change Model Under Tension of 100N

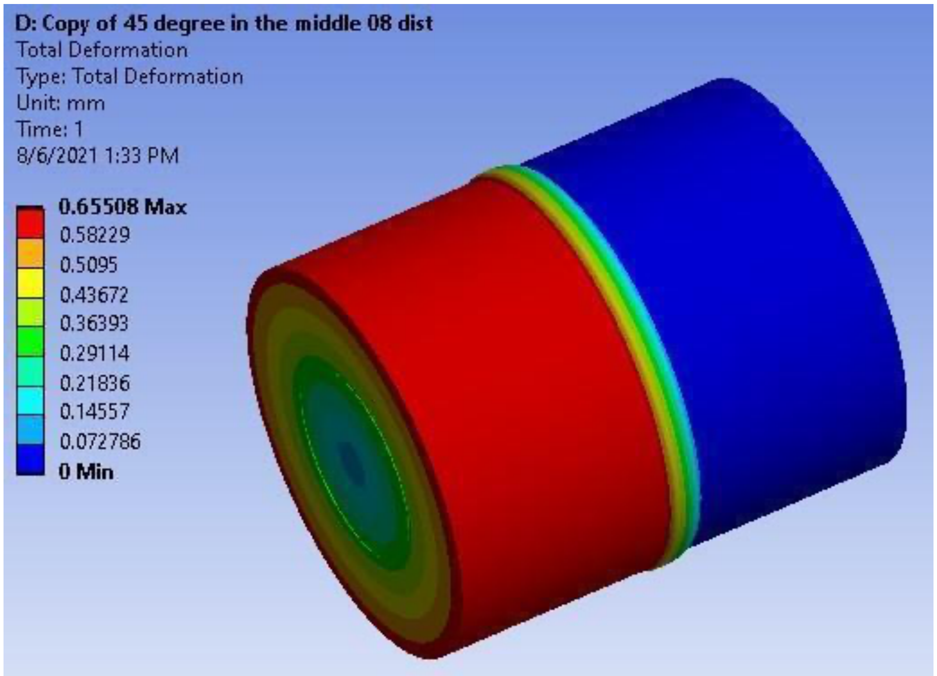

Figure 15b: Horizontal Change Model Under Torsion of 1 N.m.