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Biomechanical Analysis of the Kirschner-Wire Depth of the Modified Tension Band Wiring Technique in Transverse Patellar Fractures: An Experimental Study Using the Finite-Element Method

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Background: Modified tension band wiring is one of the most preferred surgical methods for transverse patellar fractures. However, the optimal depth or sagittal position of a Kirschner wire (K-wire) in modified tension band wiring has yet to be determined. The purpose of this study was to evaluate whether the depth of a K-wire affects the biomechanical characteristics of modified tension band wiring using the finite-element method.

Methods: A patella model was designed with a cuboid shape (length, 34.3 mm; width, 44.8 mm; and thickness, 22.4 mm) and divided into the cortical and cancellous bone parts. A transverse fracture line was formed on the midline of the cuboid shape model. The cuboidal model was applied to modified tension band wiring. The depth or sagittal position of the K-wire was divided into superficial, center, and deep. With the Abaqus v2017 program (Dassault System Inc.), the distal part of the model was fixed, and a tensile load of 850 N was applied to the proximal part of the model at an angle of 45°. The maximum pressures of the cortical and cancellous bones at the fracture plane were measured. The largest von Mises values of the K-wire and stainless steel wire were also measured. The fracture gap on the distracted or anterior side was measured.

Results: In deep K-wire placement, the highest peak von Mises values of the cortical and cancellous bones were observed. The K-wire and stainless steel wire showed the highest von Mises values in deep K-wire placement. The fracture gap was also largest in deep K-wire placement.

Conclusions: The depth of the K-wire affects the biomechanical characteristics of modified tension band wiring. Deep placement of the K-wire will be more favorable for bone union than the empirically known 5-mm anterior or center placement of the K-wire.

Keywords: *Patella, Transverse fracture, Tension band wiring*

Modified tension band wiring is one of the most preferred surgical methods for transverse patellar fractures.[1,2] The basic principle in tension band wiring is the conversion of the distraction force on the outer cortex to a compression force on the inner cortex, which is the articular side.[3] However, despite tension band surgery, previous research reported interfragmentary displacement of up to 10%–20%,[4] which may lead to 2.4%–12.5% nonunion of patellar fractures.[5] Although several factors, including depth or sagittal position of a Kirschner wire (K-wire), are known to affect the results of modified tension band wiring,[6] the optimal depth or sagittal position of a K-wire in modified

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tension band wiring has yet to be established. The purpose of this study was to evaluate whether a change in K-wire depth affects the biomechanical characteristics of modified tension band wiring using the finite-element method.

METHODS

According to the existing literature,[7] a patella model was designed in a cuboid shape (length, 34.3 mm; width, 44.8 mm; and thickness, 22.4 mm) and divided into cortical and cancellous bone parts (Fig. 1). The cortical bone had 3 mm on all sides as described in the referred literature. The Mimics ver. 13.1 software (Materialize, Leuven, Belgium) was used for modeling.

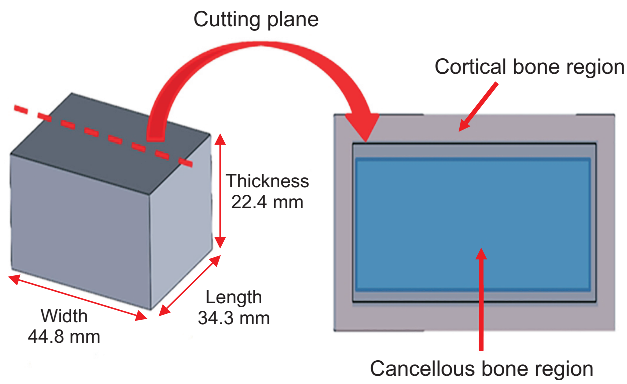

Fig. 1. The patella finite-element method model is designed in a cuboid shape (length, 34.3 mm; width, 44.8 mm; and thickness, 22.4 mm). The cortical and cancellous bone regions are designed separately.

A transverse fracture line was formed on the midline of the cuboid shape model. In the coronal view of the cuboidal shape model, K-wires were placed one-third and two-thirds from the medial border to the lateral border (Fig. 2A). In the sagittal view of the cuboidal shape model, the K-wire was placed halfway from the anterior margin to the posterior margin (Fig. 2B). This was the center position of the K-wire. An 8-tension-band wiring model was applied to the cuboid model across the fracture line. It was ensured that there was no knot of the wire or gap between the wire and the surface of the cuboid shape model (Fig. 2A and B). The K-wire was modeled as 2 mm thick, and the stainless steel wire was 1.25 mm thick. The material properties were determined on the basis of previous studies.[8,9] An elastic modulus of 1,000 MPa and a Poisson ratio of 0.3 were applied to the cortical bone. An elastic modulus of 207 MPa and a Poisson ratio of 0.3 were applied to the cancellous bone. In the case of the K-wire and stainless steel wire, the elastic modulus and Poisson ratio were set to 186.4 GPa and 0.3, respectively.

On the basis of the existing biomechanical studies,[10,11] simulation was conducted under the assumption of a 45° flexion state that shows the maximum pressure on the joint surface in a transverse fracture. The distal part of the model was fixed, and a tensile load of 850 N was applied to the proximal part of the model at an angle of 45°

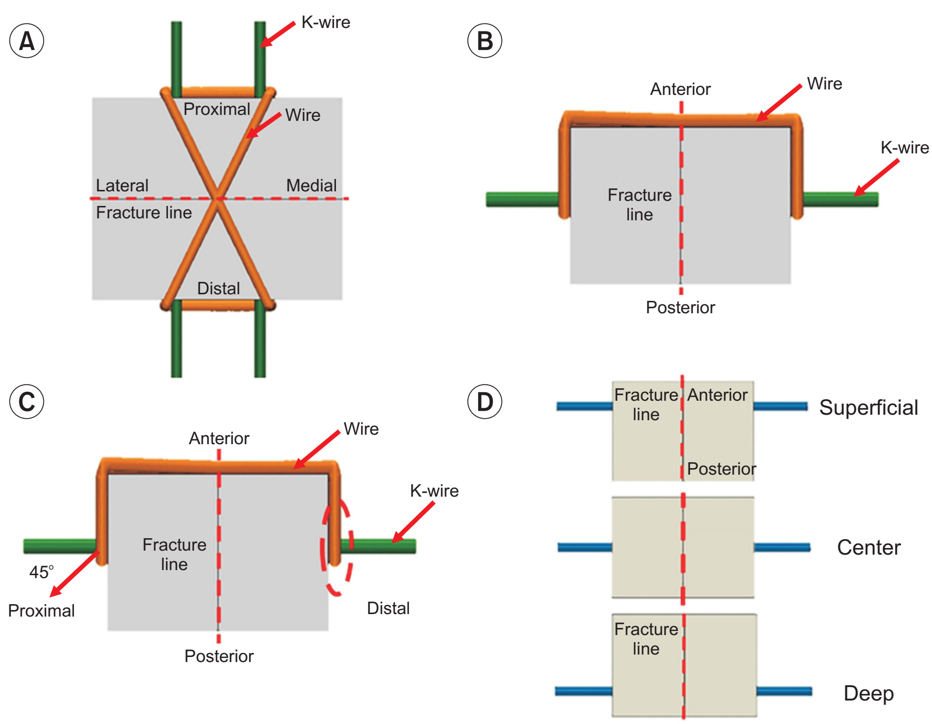

Fig. 2. (A) Coronal section of the finite-element method (FEM) model. (B) Sagittal section of the FEM model. (C) The distal part of the model is fixed, and a tensile load of 850 N is applied to the proximal part of the model at an angle of 45° during simulation. (D) Three models are divided into superficial, center, and deep according to depth of placement, respectively.

(Fig. 2C). The Abaqus v2017 program (Dassault System Inc., Waltham, MA, USA) was used for the simulation. In this study, the area where the compression force was applied corresponded to the joint surface of the patella, which was the posterior side of the cuboid shape model (Fig. 2C). In the sagittal view of the cuboidal shape model, the depth or sagittal position of the K-wire was divided into superficial, center, and deep. Superficial or deep placement was set at 5 mm away from the center (Fig. 2D).

The maximum pressures on the cortical and cancellous bones in the fracture plane were measured in the three K-wire placements. The largest von Mises values of the K-wire and stainless steel wire were also measured (Fig. 3). The fracture gap, defined as the distance of the distracted or anterior side in the sagittal view of the cuboidal shape model, was measured (Fig. 4).

RESULTS

The peak von Mises values of the cortical bone in superficial, center, and deep placement were 5.79, 8.74, and 16.48 MPa, respectively. The value was 2.84 times higher in deep placement than in superficial placement. In all the placements, the maximum von Mises value was observed on the posterior side (Fig. 3A). In the cancellous bone, the peak von Mises value was 2.36 MPa in superficial placement, 15.92 MPa in center placement, and 21.95 MPa in deep placement (Fig. 3B).

The means of the highest von Mises values applied to the K-wire and stainless steel wire were 950.05 and 1,207.29 MPa, respectively. The stainless steel wire had a greater stress than the K-wire. Both the K-wire and

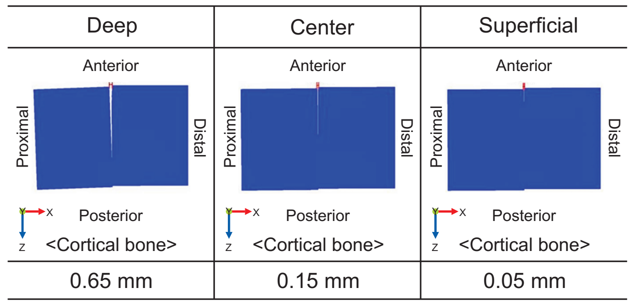

Fig. 4. Fracture gaps in deep, center, and superficial K-wire placement.

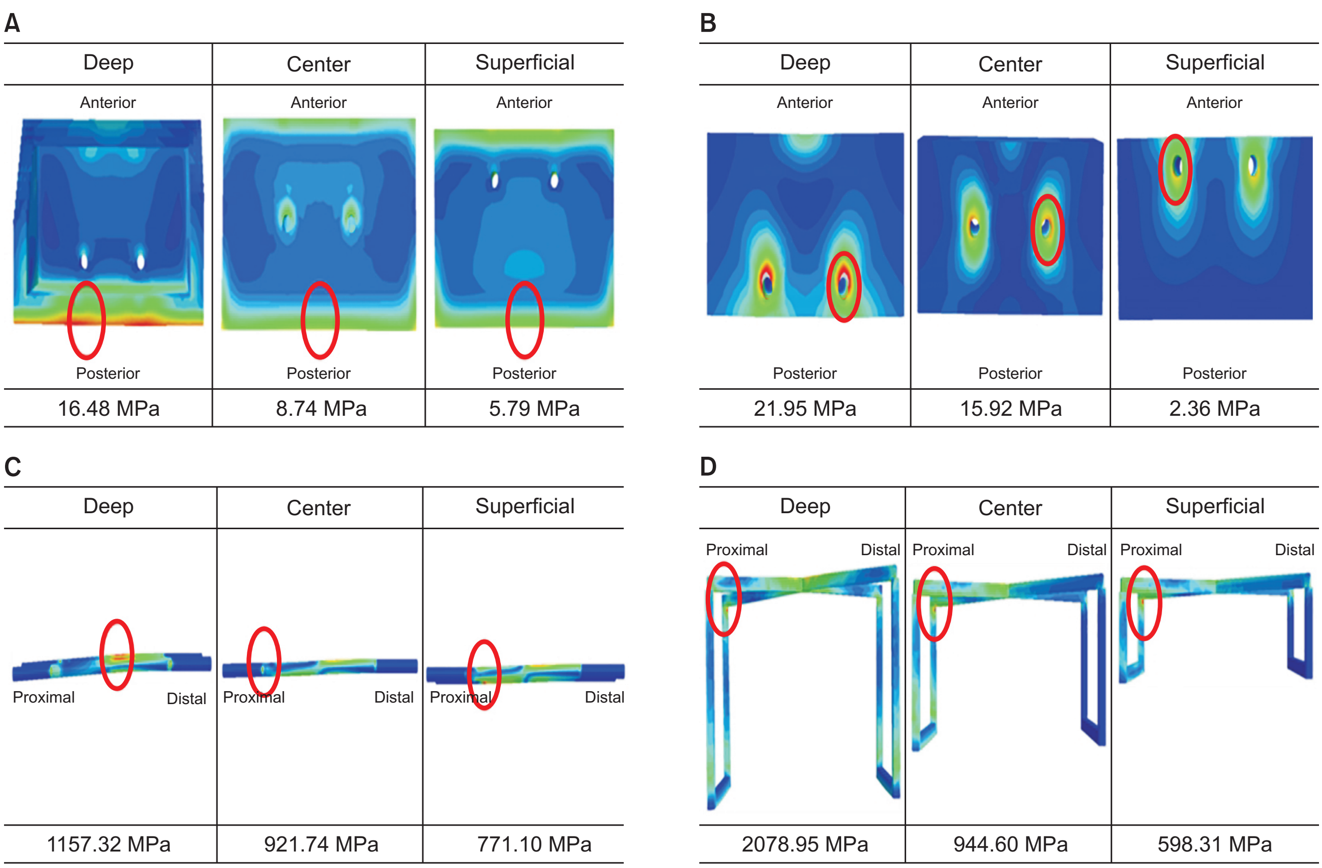

Fig. 3. The peak von Mises values of the cortical bone (A), cancellous bone (B), K-wire (C), and stainless steel wire (D). The red circles indicate the area of the peak von Mises values.

stainless steel wire showed the highest von Mises values (1,157.32 and 2,078.95 MPa, respectively) in deep K-wire placement (Fig. 3C and D). The fracture gaps were 0.65, 0.15, and 0.05 mm in deep, center, and superficial placement, respectively. The fracture gap was largest in deep placement, and it was observed on the anterior side (Fig. 4).

DISCUSSION

The most important finding of this study is that when K-wire placement was close to the posterior side or joint surface of the patella, the highest peak von Mises values were found in the cortical bone, cancellous bone, K-wire, and stainless steel wire. The area of the peak von Mises value appeared near the joint surface of the patella in all depths of placement (Fig. 3A and B). The fracture gap was the smallest in superficial placement and largest in deep placement (Fig. 4). These results show that when the K-wire was located near the joint surface of the patella, the greatest compression force occurred on the joint surface, and the fracture gap on the outer cortex of the patella was the largest. In the finite element analysis conducted by Ling et al.,[12] the average pressure of fracture surfaces was the greatest when the K-wire was inserted deeply, which is consistent with our finding. The advantage of our study is that the cortical bone and cancellous bone portions were analyzed separately.

Tension band wiring is the most commonly used method for transverse fractures of the patella. Bone union is promoted by converting the tension of the patellar ligament and quadriceps muscles into the compression force of the fracture. The K-wire serves to withstand the tension of the patellar tendon and quadriceps muscles. The stainless steel wire resists the bending force during flexion of the knee. Therefore, proper placement of the K-wire could play a key role in preventing displacement of the fracture fragment and withstanding the tension. Previous studies recommended the insertion of the K-wire either 5 mm away from the outer cortex or center of the patella.[3] However, this recommendation was not based on clear evidence and presented empirically. The theoretical background of this recommendation is insufficient.

To obtain bone union in transverse patellar fractures, absolute stability must be secured through interfragmentary compression. Absolute stability leads to primary bone healing.[13] Contact healing is known to occur earlier than gap healing in the process of fracture union.[14] Therefore, attaining contact healing of the joint surface before gap healing of the non-articular surface is reasonable. For contact healing of the joint surface, the fracture gap should be reduced as much as possible by applying a greater compressive force to the joint surface of the patella. Contact healing of the joint surface will prevent displacement of fracture fragments and progression of patellofemoral arthritis. The results of this study show that when the K-wire was placed close to the joint surface, the maximum compression force was 2.84 times higher in the cortical bone at the articular surface (Fig. 3A). This clearly shows the rationale for inserting the K-wire close to the articular surface of the patella.

The largest peak von Mises values of the K-wire and stainless steel wire vary depending on the depth or sagittal position of the K-wire. The stainless steel wire is always placed on the outer cortex of the patella. However, the depth or sagittal position of the K-wire is adjustable. Therefore, to obtain stable fracture fixation and the largest compression force, the recommended depth or sagittal position of the K-wire is as far as possible from the stainless steel wire.

Our findings are supported by a clinical study. Hsu et al.[6] showed that the superficially placed K-wires were associated with a higher rate of minor reduction loss, which may lead to malunion of the patella or an extended period of immobilization. They suggested that the superficial placement of K-wire decreases the grasped bone and holding power of the K-wire, causing minor reduction loss. In fracture gaps, when the K-wire is located close to the posterior side or the joint surface of the patella, the gap between the fractures on the outer cortex of the patella increases. However, the gap between fractures in deep K-wire placement was 0.65 mm, which was smaller than 1 mm. Considering that fracture movement of < 1 mm could promote fracture healing in previous studies,[15] a 0.65-mm fracture gap will not adversely affect bone union.

This study has some limitations that need to be considered. First, the shape of the patella was set as a square, which does not fully reflect the actual shape of the patella. However, there was consistency between the results of this study and the results of an existing clinical study.[6] Second, a difference may exist from actual tension band surgery because separation between the steel wire and the model or knot of the steel wire was not considered. Third, finite element analysis was performed only at the 45° angle. The highest peak von Mises values or fracture gap may vary at different angles. Therefore, whether the same result will be obtained in the entire knee flexion angle range in a cadaver study must be clarified.

The depth of the K-wire appeared to affect the biomechanical characteristics of modified tension band wiring. Deep placement of the K-wire will be more favorable for bone union than the empirically known 5-mm anterior or center placement of the K-wire.

CONFLICT OF INTEREST

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

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