Biomechanical effects of three different configurations in Salter Harris type 3 distal femoral epiphyseal fractures

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Abstract In this study, the biomechanical effects of three different configurations (K-wire, stainless steel screws, and titanium screws), which are used for stabilizing Salter–Harris (SH) type 3 epiphyseal fracture of distal femur after reduction process, on the epiphyseal plate and fracture line have been investigated under axial, rotational, and bending forces to determine the most advantageous configuration. Three different configurations have been modeled using SolidWorks, and computer-aided numerical analyses were performed by finite-element analysis software. For each configuration, mesh process, boundary conditions, and material model have been applied in finite-element analysis software. In addition, von Mises stress values on growth of epiphyseal plate and K-wire have been calculated. According to the results obtained, it has been found particularly advantageous to use the fixation shape of configuration with screw. In addition, the fixation shape of K-wire configuration was found to be disadvantageous in the SH type 3 epiphyseal fractures.

Keywords Salter Harris type 3 · K-wire · Finite-element analysis · Epiphyseal plate · Biomechanics

1 Introduction

The distal epiphysis fractures of femur have a high risk of especially growth delay and other morbidities [1–4]. There are some factors considered as the cause of this situation as follows. The age of the person, type of fracture, degree of shear, sinuous structure of physis, quality of fracture reduction process, and fixation shape [5–7]. It has been suggested that the main cause of angulation at the fracture line and growth complications is physeal bar formation by considering its histology [5, 8]. In the treatment of Salter–Harris (SH) type 3 epiphyseal fracture of distal femur, the fixation with partially threaded screw or K-wire applied parallel to the joint and without passing through the physis line is recommended [9, 10]. The size, number, location of the screws or K-wires used depending on decision of the surgeon can increase the physical injuries as well as the stability of fracture. Although it has been stated that the purpose of this type of fracture treatment is obtaining anatomic reduction and preventing additional injuries of the physis, the most reliable and secure technique has not been identified yet [5, 8, 9, 11]. In recent studies, it has been shown that an injury with a 7–9% ratio in cross-sectional area of the physis line can disrupt the growth [12, 13]. The aim of our study is investigating the biomechanical effects of two Kirschner wires and one partial threaded screw (stainless steel and titanium), which are used for stabilization of Salter–Harris (SH) type 3 epiphyseal fracture after reduction, on the epiphyseal plate and the fracture line under axial, rotational, and bending forces and also identifying the most advantageous configuration. In particular, the case, in which the least stress
occurring on the epiphyseal plate and the best stability in the fracture lines, has been investigated.

2 Computer-aided finite-element analysis and modeling

2.1 Three-dimensional modeling (3D)

The human femoral model was scanned using 3D scanner and point cloud was obtained. After that, 3D model of femur was created using point cloud data by Geomagic Studio 10 program. This femur model was scaled for taking femur dimensions of a child into account, and SH Type 3 fracture for different configurations was created using SolidWorks program, as shown in Fig. 1. The diameter of K-wires used in configuration was Ø2 mm and the diameter of screw was Ø4 × 1.75 × 22 mm cancellous screw, respectively (Fig. 2).

2.2 Finite-element analysis (FEA)

The computer-aided numerical analysis used for stabilization of three configurations after reduction process during fixation was performed using AnsysWorkbench software. 3D CAD models of two configurations (Fig. 1) were imported into AnsysWorkbench software to prepare
the FEA. Load, boundary conditions, and material models were defined in AnsysWorkbench.

2.3 Loading and boundary conditions

The mesh process was performed using hex dominant finite element for FEA modeling after importing two different configurations of 3D models into AnsysWorkbench software (Fig. 3). FEA model has 213,202 nodes and 64,084 elements. While the mesh density for femur and femur fragments was inputted as 1.5 mm, K-wires, epiphyseal plate, and screw were inputted as 0.5 mm. Axial, bending, and rotational loading were applied within two configurations.

A load of 350N in axial direction was applied to the femoral head, and it was fixed from the epiphyseal plate for axial loading, as shown in Fig. 4. According to this figure, bending forces were applied to the epiphyseal plate in varus and valgus directions, and femur was fixed from metaphysis and diaphysis part. In addition, bending forces were applied to the epiphyseal plate in anterior and posterior directions, and femur was fixed from metaphysis and diaphysis part. Finally, torsional force was applied to the epiphyseal plate around the z-axis in CCW, and femur was fixed from metaphysis and diaphysis part.

Contact types between bone and bone interaction, K-wires and bone interaction or screw and bone interaction were defined as a frictional contact. Friction coefficients were taken as 0.46 for bone and bone interactions and 0.42 for K-wires and bone interaction or screw
and bone interaction, respectively [14]. The contact type between epiphyseal plates was defined as a frictionless contact. In addition, the contact type between epiphyseal plate and bone was defined as bonded [15]. Finally, as it can be seen in Fig. 5, convergent analysis was conducted. The force convergence was commonly used in non-linear analyses. If solution is not convergent, there is a problem. For a good solution, purple line on the convergent graph should be acted on the cyan line. This status is dependent on the boundary conditions, such as friction, contact type, and others.

2.4 Material model

Mechanical properties of bone and epiphyseal plate used in the finite-element (FE) analyses were given in Table 1. While stainless steel was selected for K-wires used in FEA, both stainless steel and titanium alloy were selected for screw. Mechanical properties of screw were obtained from AnsysWorkbench Material Library [16]. Linear isotropic material model was used for mechanical behaviors of K-wires, bone, epiphyseal plate, and screw. The elasticity modulus of the epiphyseal plate was assumed as soft tissue when compared with other materials.

3 Results

After entering the loading and boundary conditions, FE analyses were solved. According to FEA results, maximum stress values on epiphyseal plate upon FEA results, K-wires, and screw are given in Tables 2 and 3, respectively. These stress values were evaluated according to von Mises criteria. The von Mises model is generally used in ductile materials. As shown in Table 2, while the highest stress values on physis line under different loadings were occurred in bending and torsional forces in the frontal, sagittal (varus–valgus angulation, anterior–posterior angulation, and displacement) and transverse plane, respectively, in screw configurations; the lowest stress values were occurred in bending and torsional forces in the frontal, sagittal (varus–valgus angulation, anterior–posterior angulation, and displacement), and transverse plane, respectively, in K-Wires configuration. Considering the axial forces in the fracture line, more stress was found on K-wires configuration in physis. In Table 3, it has been seen that stress values are higher in K-wires compared to screws. Stress distributions occurring in epiphyseal plate under axial loading in various configurations are shown in Fig. 6. The stress distributions occurring in epiphyseal plate under bending (varus, valgus, anterior, and posterior) and torsional loadings are shown in Figs. 7, 8, 9, 10 and 11, respectively.

![Fig. 5 Convergence analysis](image-url)
Discussion

In the treatment of femur distal epiphysis SH type 3 fractures, parallel screw or k-wires between physis and joint can be used [8–10]. However, there is no bio-mechanic evidence showing that which one is stronger in fracture stability in fixations done with screw or K-wires. In addition, in these fixations, issue about in which technic stress load applied on the physis under force is less or more is still not very clear. In our study, when displacive forces reflected to fracture in physis line evaluated; the lowest stress values in bending forces in the frontal and sagittal plane (varus–valgus angulation, anterior–posterior displacement, and angulation) and the torsional forces in the transverse plane were found using K-wires configuration in physis line. This conclusion leads us to think that K-wires undertake stress in fracture lines. In fact, finding higher stress values in K-wires supported this conclusion (Tables 2, 3). It was also supported by calculating lower stress values on screws (except stainless steel in posterior bending) while they were higher in fracture line under bending, and torsional forces (Tables 2, 3) Considering the axial forces in fracture line, it has been ascertained that physis was crushed by being subjected to more compression and was exposed to axial stress in K-wire configurations. When we look at the literature, there is not any study about at which rate physis carries the load after which fixation. When one considers that an epiphyseal fracture that has the worst prognosis is the type of crush in physis line, it has been thought that configuration, in which the axial stress in physis line is greatest, is the worst [19]. From this point of view,

| Table 2 | Stress values occurring in epiphyseal plate |
|---------|-------------------------------------------|
| No | Fixation type | Epiphyseal plate |
| | | Axial | Bending (varus) | Bending (valgus) | Bending (anterior) | Bending (posterior) | Torsional |
| 1 | Parallel K-wires (MPa) | 3.52 | 0.87 | 0.95 | 0.88 | 0.97 | 0.16 |
| 2 | Screw stainless steel (MPa) | 3.42 | 1.03 | 1.07 | 1.18 | 1.16 | 0.18 |
| 3 | Screw-titanium alloy (MPa) | 3.42 | 1.03 | 1.08 | 1.18 | 1.15 | 0.18 |

| Table 3 | Stress values occurring in K-wires and screws |
|---------|--------------------------------------------|
| No | Fixation type | K-wires and screw |
| | | Axial | Bending (varus) | Bending (valgus) | Bending (anterior) | Bending (posterior) | Torsional |
| 1 | Parallel K-wires (MPa) | 134.64 | 98.17 | 100.86 | 99.96 | 98.54 | 98.38 |
| 2 | Screw stainless steel (MPa) | 113.65 | 88.24 | 88.43 | 92.04 | 106.34 | 87.33 |
| 3 | Screw-titanium alloy (MPa) | 87.72 | 83.22 | 83.26 | 71.71 | 96.83 | 73.96 |

Fig. 6 Stress values occurring at different configurations under the axial loading. a K-wire, b stainless screw, and c titanium screw
K-wires were considered as disadvantageous, because they caused more crush in physis line. We can explain why the stress appeared in the K-wires under axial load was higher than the stress appeared in the screw by the surface area affected by the force. Axial load is applied to K-wire, which is 2 mm in diameter, and screw, which is 4 mm in diameter, respectively.

In addition, other remarkable items are stainless steel and titanium screws. Considering the stress values in the physis line given in Table 2, it has been seen that stress values in the epiphysis obtained using stainless steel or titanium screws configurations are almost equal to each other. However, considering the stress values on screws, lower stress values were found on titanium screws. This can be explained by higher yield and tensile strength of titanium compared to stainless steel. Salter et al. have stated that since excessive manipulation performed for good reduction quality may put excessive load to the epiphysis, it should not be applied. They also suggested that unsuitable reduction of epiphysis can be preferred rather than putting excessive load to the epiphysis plate and the morbidity that will accordingly develop should be treated in the late-term [20].

It has been stated that growth delay may depend on the fracture type or differences in the size of K-wires; developing physeal bar is also responsible for this growth delay.
[8, 9]. This situation in the healing period, in which bone-bridge occurs in physis, might be related with the stress applied to physis plate by K-wire or screw, which are used for stabilization. We think that, apart from the type of epiphyseal fracture, also the differences of force applied to physis line of the variety or configuration of implants used for fixation may be effective in the bar formation, because we know that increasing deformation in physis results in increased morbidity. Accordingly, we also consider that when the method with more axial load on the physis line is used, the physeal injury will be more severe; therefore, this will be responsible for more bar formation occurring at this area. There is not an exact evidence or biomechanical study stating that which factors are effective on the formation of iatrogenic epiphysiodesis at this area (bar formation which causes growth delay).

According to a study conducted by Garrett et al. [21], SH classification is the prognostic indicator and the use of K-wire goes through percutaneous and physis is not related with growth delay. On the contrary, in many studies, it is suggested that growth delay is also related with fracture type fixation shape [22]. We think that—as in several studies, one of the indicators that will affect the result is the technique used for the fixation; causing deformation...
in epiphysis in different severities that might be related to growth delay by this way. Our results indicate that stability is better in parallel K-wire configuration; however, it is disadvantageous because of causing more deformation in epiphysis. We believe that SH type 3-epiphysis fracture of distal femur fixation should be performed by screws instead of two parallel K-wires.

5 Conclusion

In this study, the biomechanical behaviors of three different configurations (K-wire, stainless steel screw, and titanium screw) used for stabilization after reduction in SH type 3 epiphyseal fracture of distal femur under axial, rotational, and bending forces on epiphyseal plate and fracture line are investigated, and we tried to find out which of the configurations is more advantageous to use. According to FEA results, it has been found particularly advantageous to use fixation type in screw configuration. In addition, in SH type 3 epiphyseal fracture, fixation type is found to be disadvantageous in K-wire configuration. The mechanical properties the bone and the epiphyseal plate were considered as isotropic material in this study. This case is a limitation for this study. We are planning to perform a new study using orthotropic properties of bone and epiphyseal plate.

Compliance with ethical standards

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Conflict of interest  There is no conflict of interest.

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Fig. 11 Stress values occurring at different configurations under the torsional loading. a K-wire, b stainless screw, and c titanium screw
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