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Effect of the screw tightening sequence on the stress distribution of a dynamic compression plate: A pilot finite element study

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Abstract

Objective: Although the optimal screw tightening sequence is a common question orthopaedists encounter during fractures fixation with a dynamic compression plate (DCP), the effect of the screw tightening sequence on the stability of the plate has never been explored. This study explores the effect of the screw tightening sequence on the stress distribution of a DCP using a finite element method. **Methods:** Idealized finite element analysis models of the femoral diaphysis with six-hole or eight-hole DCPs were constructed. The screw tightening preload was simulated using 'bolt load' in ABAQUS. Two screw tightening sequences were studied for the six-hole plate and six sequences were studied for the eight-hole plate. U magnitude and Von Mises stress were used to evaluate the deformation and stress distribution of the plate, respectively. Deformation and stress distribution plots from different sequences were compared. **Results:** The different screw tightening sequences showed different deformation processes, while all had the same final deformation after all the screws were tightened. Each screw tightening step of different tightening sequences showed different stress distributions in the plate, while all had the same stress distribution after all the screws were tightened. **Conclusion:** Using different screw tightening sequences to fix the same DCP can produce the same stability, which means in terms of fixation stability, after the two screws nearest to the fracture line are tightened, surgeons do not need to hesitate about the order in which the rest screws should be inserted during the surgery.

Keywords

dynamic compression plate, finite element analysis, screw tightening sequence, stress distribution

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Introduction

Although locking plate fixation is becoming increasingly popular for comminuted and osteoporotic fractures, the dynamic compression plate (DCP), which is designed to achieve compression across the fracture site, remains the standard choice for simple diaphyseal fractures and some wedge fractures.[1] The main advantage of DCP is the absolute stability achieved from the dynamic compression unit that can provide a stable environment for bone healing. Many researchers have focused on the effect of the number of screws, the screw configuration, the types and length of the plate, the dynamic compression units that are used to get compression across the fracture line, and the fracture gap on the mechanical stability of the bone-DCP system,[2–7]

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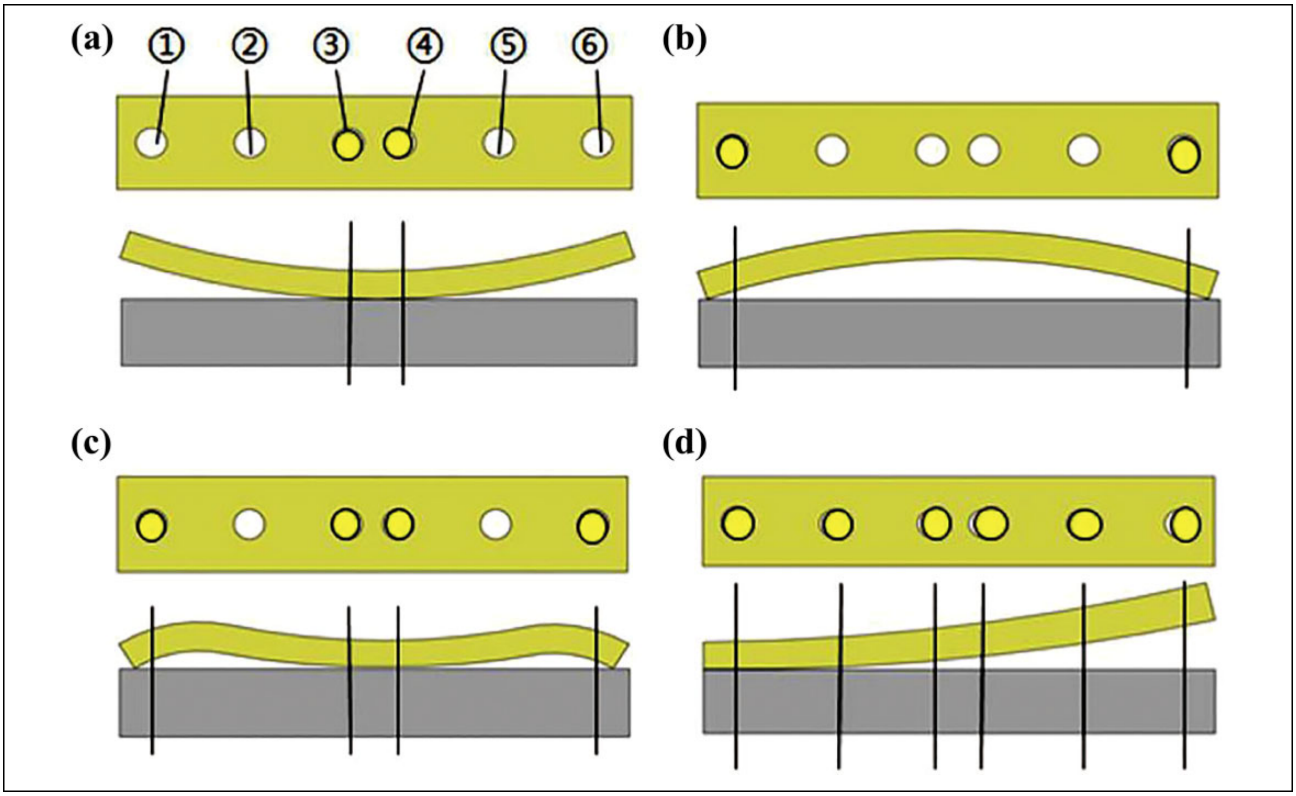

Figure 1. Schematic of the different deformations of DCPs caused by different screw tightening sequences. DCP: dynamic compression plate. (a) The two ends of the plate will tilt upward if the central two screws are tightened first. (b) The middle part of the plate will bend up if the screws at the two ends of the plate are tightened first. (c) If we then tighten the central two screws, high stress will occur around screw hole ② and ⑤. (d) The plate seems to have less stress concentration if the screws are tightened from ① to ⑥.

but no attention has been given to the effects of the screw tightening sequence on the mechanical stability during surgery.

Unlike a locking compression plate (LCP) which uses locking screws that have a threaded head enabling the screw to fasten into the plate as well as into the bone, a DCP uses compression screws to press the plate to the bone directly.[8] The friction between the plate and the bone that comes mainly from the pressure of the screw head is the source of stability of the DCP. Therefore, stress exists in the bone-DCP system before physiological loads are applied, whereas no stress is seen on the tightened locking screws. In terms of the DCP (Figure 1), we can image that when the two screws nearest to the fracture line are tightened first (③and④), the plate will have a micro-deformation such that the two ends of the plate tilt upward (Figure 1(a)). However, if we tighten the screws at the two ends of the plate first (①and⑥), the middle part of the plate will bend up (Figure 1(b)); if we then tighten the middle two screws, high stress might probably occur at the part of plate around screw hole ②and⑤ (Figure 1(c)). The screw sequence in Figure 1(d) (tightening sequence from ① to ⑥) seems to be more reasonable than that has less stress concentration on the plate. Stress concentration on the plate is what we try to avoid during fracture fixation, which is the main reason of plate breakage.[9,10] Screw tightening sequence may be one of the causes of stress concentration that we neglect.

When a compression screw is tightened, the plate will have a micro-deformation that leads to stress distribution in the plate. Therefore, this study hypothesizes that different screw tightening sequences might lead to different deformations in the plate, and then different stress distributions occur. To verify the hypothesis, this study uses finite element simulation, which permits detailed evaluation of the stress distribution in the plate; this is difficult or even impossible to measure in a laboratory biomechanical experiment. If the hypothesis is tenable, we will proceed to investigate the optimal screw tightening sequence for DCP fixation.

Materials and methods

To explore the effect of screw tightening sequence on stress distribution in DCPs, standard and simplified models were used. This study seeks to explore the effect in two most commonly used DCPs, the six-hole plate and eight-hole plate. Quasi-static (implicit, standard) analyses were conducted using geometric nonlinearity in ABAQUS 6.10 (SIMULIA, Providence, Rhode Island, USA).

FEA model

Two idealized geometric models of the femoral diaphysis were constructed using an extruded cross section. The geometric characteristics of the bone were selected to represent the femur of healthy young adults, whose diameter is 25 mm and cortical thickness is 5 mm. The length of femur model for the six-hole plate was 72 mm and 96 mm for the eight-hole plate. To simplify the model, no fractures were made in the diaphysis models to imitate the compression process. The six-hole plate and eight-hole plate were constructed to have a thickness of 3.6 mm, a width of 10 mm, hole spacing of 12mm and the contour fit completely with the femur model. The compression screws we built were simplified screws with a diameter of 3.8 mm, without threads.

Real bone is an anisotropic and heterogeneous material.[11] However, since the stress on the bone is not the main focus of our study, the bone properties used in this study were simplified as linear elastic, homogeneous and isotropic materials. Because the bone models in this study were used to represent the femoral diaphysis, only cortical bone was included in the models. Young's modulus and Poisson's ratio for cortical bone are 16.8 GPa and 0.3, respectively. The plate and screws were homogeneous, isotropic and linear elastic steel. Young's modulus for both was 180 GPa.[12–15] Poisson's ratio for steel was taken as 0.3.[2,12,14]

To simplify the simulation, the screw–bone interaction was modelled as tied. The plate–bone interaction for the DCP used a frictional coefficient of 0.4 based on some of the recent studies.[8,16]

The screw tightening preload was simulated using 'bolt load' in ABAQUS 6.10 (SIMULIA), which has been proved to be the representative of compression screw tightening.[17] This preload was applied to a slice of the screw shaft, below the screw head and above the surface of the bone. Values of preload vary widely in the literature;[8,16,18–20] a value of 500 N was chosen based on an average of some previous studies.

Since stress distribution in the plate is our main concern, quadratic tetrahedral elements were used for the plate, while linear tetrahedral elements were used for the bone and screws. The approximate number of elements used in the plate, the bone, and each of the screws was 35,200, 35,000 and 5,800, respectively, for the six-hole plate–bone system, and 47,100, 46,700 and 5,800, respectively, for the eight-hole plate–bone system. Both modes had refinement at the plate. The average element edge length around the screw holes was 0.02 mm. A mesh convergence study was conducted, and appropriate mesh resolutions for different parts of the model were determined based on their influence on the highest Von Mises stress (VMS) on the plate. Doubling the number of elements in the bone, plate and screws changed the highest VMS on the plate by 1.76% for the six-hole plate and 2.13% for the eight-hole plate. As a consequence, the FE model with the above stated number of elements was considered to be appropriate for analysis.

Tightening sequence

During the fixation of simple fractures with DCPs, the two compression screws nearest to the fracture line have to be tightened first to get compression across the fracture line. So, in this simulation study, the central two screws were tightened first. If the remaining screws are then tightened in a symmetric sequence across the fracture line, then the different permutations give two sequences for the six -hole plate and six sequences for the eight-hole plate (Figure 2(a)).

Deformation

U magnitude is an output in ABAQUS to show the displacement of the model. It is an integrate value of displacement in all directions, which can show deformation of the model correctly. So it was used to evaluate the deformation of the plate. U magnitude plots of the plates of each tightening step from different sequences were compared.

Stress distribution

VMS is used widely in the industrial realm to evaluate the failure of materials, especially ductile materials. So VMS distribution plots of the plates of each tightening step from different sequences were compared. The values of VMS at the middle point between each of the screw holes from different screw tightening sequences were measured. The values were compared between different tightening sequences.

Results

All the tightening sequences were simulated successfully using ABAQUS. Figure 2(b) shows the simulated tightening process of one of the screw tightening sequences (seq. 1) of the six-hole plate.

Deformation

The deformation plots on the six-hole plate and eight-hole plate for different screw tightening sequences are shown in Figures 3 and 4, respectively.

For both the six-hole plate and eight-hole plate, when the first two central screws were tightened, the plate had micro-deformations such that the two ends of the plate tilted. The basic deformation pattern for a tightened screw is that the plate around the tightened screw tilted.

The different tightening sequences showed different deformation processes, while all had the same final deformation after all the screws were tightened.

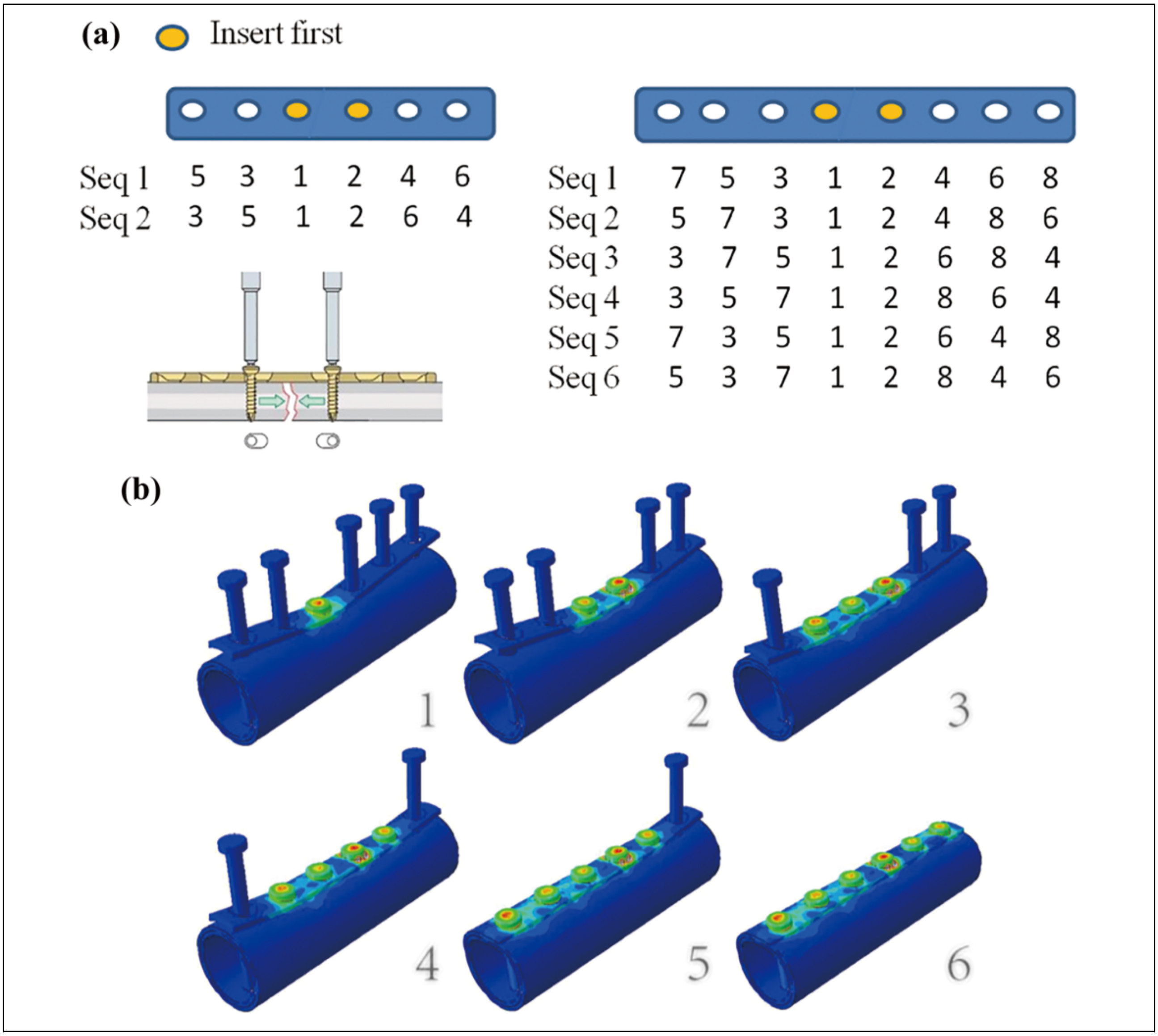

Figure 2. (a) Different screw tightening sequences for the six-hole plate and the eight-hole plate. (b) Screw tightening sequence 1 of the six-hole plate.

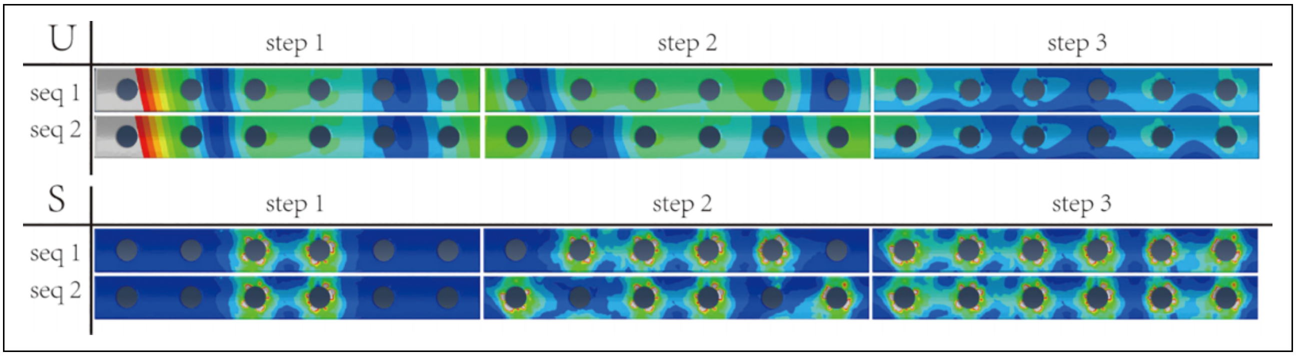

Figure 3. Deformation and stress distribution for different screw sequences on the six-hole plate. In each step, two screws were tightened in symmetrical screw holes.

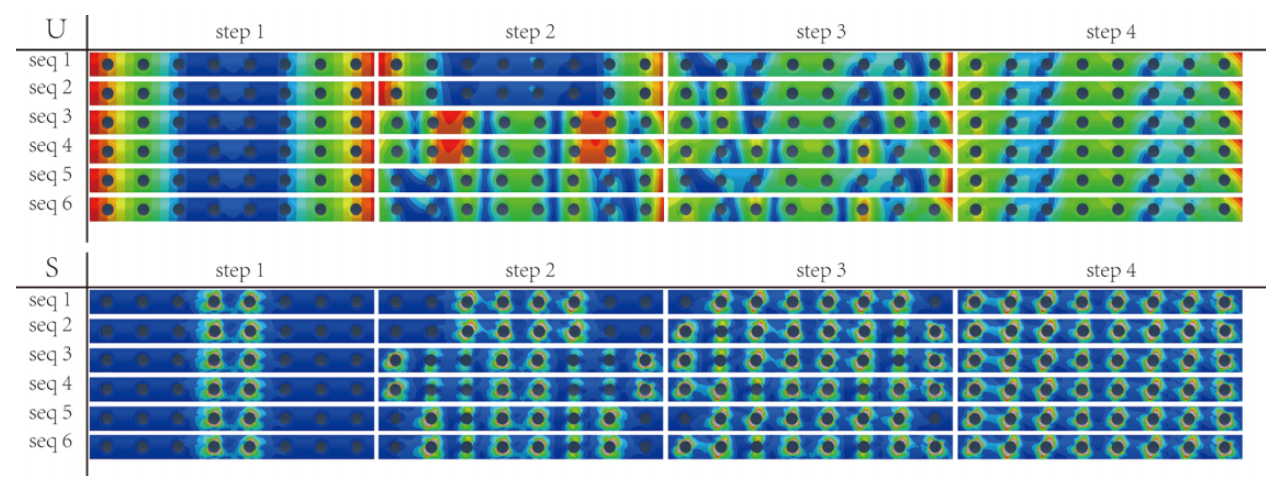

Figure 4. Deformation and stress distribution for different screw sequences on the eight-hole plate. In each step, two screws were tightened in symmetrical screw holes.

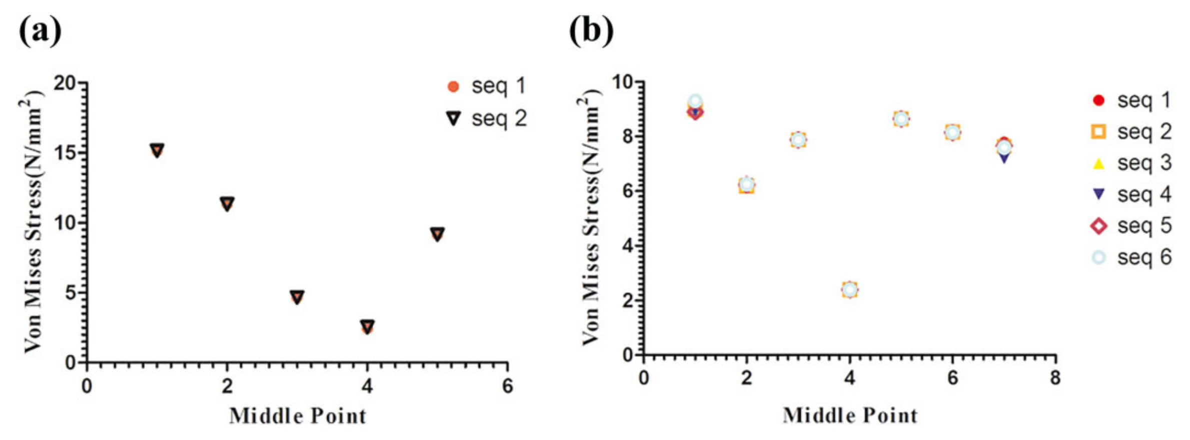

Figure 5. Value of at the middle point between each screw hole for the different screw tightening sequences. (a) VMS of the six-hole plate. No difference was found between the different sequences. (b) VMS of the eight-hole plate. The value for different sequences was slightly different at the two ends of the plate. VMS: Von Mises stress.

Stress distribution

The stress distribution plots on the six-hole plate and eight-hole plate for different screw tightening sequences are shown in Figure 3 and Figure 4.

The stress level is high around the screw hole where the screw head is pressed to the plate. Each screw tightening step of the different tightening sequences showed different stress distributions on the plate, while all had the same stress distribution after all the screws were tightened.

The difference between the values of VMS at the middle point between each of the screw holes for the different screw tightening sequences are shown in Figure 5. For the six-hole plate, the stress values at each position for the different tightening sequences are almost the same. However, for the eight-hole plate, the stress values for the different tightening sequences are slightly different at the two ends of the plate, while there was no significant difference between these values ($p < 0.05$).

Discussion

Rigid internal fixation with a DCP using AO/ASIF techniques has been the standard of care for the treatment of simple long bone fractures.[1] This technique allows absolute stability of the fracture, which leads to direct endosteal bone healing. The stability of the DCP is so important that many researchers have reported the affecting factors.[2–7] Even the AO/ASIF Manual of Internal Fixation has a guideline for how to get stable fixation of specific fractures using a DCP, such as the basic principle of how many screws and what length of the plate should be used for an ulnar fracture. However, among all the affecting factors and principles, none are related to the screw tightening sequence. The effects of the screw tightening sequence on the mechanical stability of the DCP fixation are still unclear.

The screw tightening sequence is a common problem that orthopaedists encounter during fracture fixation using a DCP. There is no doubt that the first two screws nearest to the fracture line must be tightened first to get compression across the fracture site. Hence, the first two screws nearest to the fracture line are commonly tightened first to get compression across the fracture site. The tightening sequence of the first two screws is not important in transverse fractures, but it matters in the oblique fractures for reduction purpose. The AO manual had stated clearly the insertion sequence of these two screws in oblique fractures for reduction purpose. The first screw should insert in neutral position to attach the plate to the fragment which can form an axilla beneath the plate. The second screw is then inserted in eccentric position into the opposite fragment after this fragment has been reduced into the axilla. So screw insertion order can play role in gaining and maintaining reduction. However, the rest of the screws are usually tightened randomly according to the experience of the surgeons or for the convenience of the surgery without knowing whether different tightening sequences affect the stability or not. However, for tightening sequence of the rest of the screws, there is no firm evidence on the effect of screw tightening to guide surgical decisions. Our study objectively analysed the effects of the screw tightening sequence on the stress distribution of DCPs using finite element analysis (FEA), hoping to provide orthopaedists with more knowledge on this unstudied area.

Finite element method is an engineering tool for structural analysis that has been used for many years to assess the stress distribution and micro-movement of bone and implant systems. Finite element modelling can provide detailed information, such as stress distribution, that can be difficult or impossible to measure in a physical experiment, which is very suitable for us to detect the stress distribution in the plate. ABAQUS 6.10 is a software suite for FEA and computer-aided engineering. It is very a powerful tool used widely in the automotive, aerospace and industrial products industries to analyse and optimize the structure strength of different physical objects. Since FEA became popular in orthopaedic research, ABAQUS has been used widely in comparing the fixation stability of different fixation methods.

Instead of simulating the real scenario of compression of the fracture site with the two compression screws inserted eccentrically into the dynamic compression unit of a prebended DCP, which greatly increases the amount of calculation and processing time, we used the intact diaphysis model with the central two screws tightened in neutral position of the dynamic compression unit of an unprebended DCP first to simplify the simulation in this study. Since this study focuses on the stress distress distribution in the DCP, the simplified model without a fracture can work the same in a great extent as the complicated model with a fracture. What is more, as the screws inserted with different sequences in this study were screws outside the area between the first two inserted screws, the effect of the different screw sequences also happens outside this area, having a fracture in the model or not might not have much effect on the result.

The result of this study verifies part of our hypothesis that tightened compressing screws can cause microdeformation and stress distribution in the plate. This study found that the first two tightened central screws can cause tilting of the two ends of the plate, which might explain why we have to pre-bend the DC plate before fixation. This could also in turn verify the rationality of our FEA model.

The result shows that screw tightening sequence does not affect the stress distribution in the plate, which fails to verify our hypothesis that different screw tightening sequences might lead to different deformations and stress distributions in the plate. This study detects the stress distribution in the plate as an indirect index to determine the stability. Although stress distribution and stability are two totally different concepts, there is a relationship between them. A higher stress concentration of the same fixation system means that a lower load is needed to break the fixation, which leads to lower stability. So, if the bone-DCP system has stress concentration before physiological load is applied, the stability will be impaired. Therefore, we can conclude from this FEA study that using different screw tightening sequences to fix the same DCP can produce the same stability, which means in terms of fixation stability, after the two screws nearest to the fracture line are tightened, surgeons do not need to hesitate about the order in which the rest screws should be inserted during the surgery. This result is quite surprising and different with our previous reasoning (Figure 1). However, the result we obtained in this study is explainable. We know that the plate in this study is in the elastic phase during the screw tightening process. Although different screw tightening sequences lead to different deformation processes during the screw tightening process, the different sequences will result in the same deformation after all the screws are tightened. Since the plate does not undergo plastic deformation during the fixation process, all screw tightening sequences will result in the same stress distribution in the end.

We also found in this study that the eight-hole plate has larger variation of the exact values of VMS at the two ends of the plate than the six-hole plate. Maybe plate length is an important factor in the study of the effect of screw tightening sequence on stress distribution of the plate. Further investigation will be done on that.

However, the current study has some limitations. First, the model used in this study is a simplified model compared to the real DCP fixation process. Simple fracture fixation using DCPs in clinical situations is more complex than portrayed in our model. However, we made a simplified model to make the computation feasible, while still close to the real scenario. To further prove our findings, a more complicated FEA that is identical with the reality in DCP fixation surgery will be performed in the future. Second, we tightened each screw to its largest torque at one time in this study, which might not be the same procedure as in the real surgery where the screws are tightened several times. The effect of different tightening ways should be explored in the future. Third, this study only investigated the effect of screw tightening sequence on stress distribution of a DCP on the femur of healthy young adult with one plating technique, hoping to get conclusions that can apply to all kinds of DCP fixation for different long-bone fractures. Further simulation on other long bone models, such as a radius, ulna or tibia, of different bone qualities with different plating techniques should be performed to validate the finding of this study. Finally, the conclusion that the stability of the DCP fixation is not affected by the screw tightening sequence is based on the precondition that the plate is still under elastic deformation during the screwing process in this FEA study. However, the result is not applicable to situation when the plate, for example, the reconstruction plate, is under plastic deformation when the screw is tightened. How does the screw tightening sequence affect the stress distribution of the plate that under plastic deformation is still unclear. More investigations should be done on that.

Conclusion

Based on our FEA, using different screw tightening sequences to fix the same DCP can produce the same stability, which means in terms of fixation stability, after the two screws nearest to the fracture line are tightened, surgeons do not need to hesitate about the order in which the rest screws should be inserted during the surgery.

Author contributions

XF and WQ contributed equally to this work.

Declaration of conflicting interests

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