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SHORT COMMUNICATION

Biomechanical analysis of the computer-assisted internal fixation of a femoral neck fracture

Hui Lu [a], Hongquan Shen [b], Shuqing Zhou [b], Weidong Ni [a], Dianming Jiang [a],*

[a] *Department of Orthopedic Surgery, The First Affiliated Hospital of Chongqing Medical University, 1 Youyi Rd, Chongqing, 400016, PR China*
[b] *Department of Orthopedic Surgery, Jiang Jin Central Hospital of Chongqing, 725 Jiangzhou Avenue, Jiang Jin District, Chongqing, 402260, PR China*

Abstract The number and spatial configuration of the screws will affect the stability and prognosis of the fractures. In our study, we assessed the biomechanical effects of the double-head cannulated compression screw (DhCCS) and ordinary cannulated compression screw (OCCS) for the treatment of femoral neck fractures by using computer finite element analysis. The original digital imaging and communications in medicine (DICOM)data of a proximal femur were imported into Materialise's interactive medical image control system (MIMICS) software for modeling. Both DhCCS and OCCS 3D-models were obtained by using the 3D scan technique. Using the fracture model and internal fixation assembly model with an inverted triangle, two horizontal and vertical distribution were established in UG software. Next, the displacement and stress distribution were calculated in ANSYS software. The displacement value of the femoral head in the DhCCS group was smaller than that in the OCCS group, and the displacement value in the two horizontal groups was smaller than that in the vertical group. The stress distribution in the DhCCS group was concentrated on the screw rod at the fracture block and thread end, while only at the fracture block in the OCCS group. The stress in the horizontal group was more dispersed on the screws than that in the vertical group. DhCCS has reliable stability for the fixation of femoral neck fractures and applied in the clinical work and 2 horizontal fixation can be used when two screws are selected.
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* Corresponding author.
  E-mail address: jdm195910@163.com (D. Jiang).
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Introduction

Hip fracture is a common trauma. According to Gullberg's statistics, in 1990, hip fractures occurred in approximately 1.26 million elderly people worldwide. It is estimated that this number will increase to 2.6 million people by 2025 and 4.5 million by 2050.[1] Femoral neck fracture accounts for 3.6% of the total number of body fractures and 53% of hip fractures.[2] With the development of society, an increasing number of patients with have sustained high-energy injuries, and the incidence of femoral neck fractures in children and young adults has also increased gradually. Although many kinds of methods to treat femoral neck fracture have emerged, associated complications remain to be resolved clinically. Many researchers have reported that the two major complications following surgical internal fixation of femoral neck fracture are avascular necrosis of the femoral head (AVN) and bone nonunion.[3–5] Currently, internal fixation remains the gold standard for the treatment of young femoral neck fractures and non-displaced femoral neck fractures in the elderly. Moreover, cannulated compression screws are widely used because they can provide the best treatment results, and the treatment principles are early anatomic reduction, fracture end compression and strong internal fixation.[6,7] To obtain good biomechanical stability, both compression and strong internal fixation of the fracture provide conditions for first-stage fracture healing. Therefore, it is very important to determine the biomechanical stability and scope of application of the appropriate internal fixation in clinical practice.

In this study, MIMICS software was used to establish the proximal femur model, and 3D scan technology was used to obtain the DhCCS and OCCS models. ANSYS software were used for biomechanical analysis. We proposed to explore means to obtain more accurate finite element analysis of the two types of screws utilized and the different spatial configurations applied for fixation of femoral neck fractures (Pauwels Angle 60°). Thus, the femoral neck fracture biomechanical stability of the two types of screws used in fixation and the similarities and differences of spatial configuration are obtained, and we provide a theoretical basis to select the appropriate screw type and spatial layout in the clinic.

Methods

Acquisition of the proximal femur model

Thin-layer (1-mm slice thickness) computed tomography (CT) was performed on the proximal femur of a healthy adult volunteer (male, 30 years old, height = 165 cm, weight = 60 kg, excluding lesions of the proximal femur and hip joint by X-ray), and the primary DICOM data were obtained. The data were imported into MIMICS software (Materialize Company, Leuven, Belgium), and the view direction was set. The sagittal plane, coronal plane and cross section were defined, and multiple DICOM data were sequentially laid out. Grayscale images, including bone tissue, muscle and background images, could be obtained in the interface. First, the image was preprocessed to improve its resolution and smoothness. Of particular note, the discontinuous area inside the bone marrow cavity must be removed, and the selection tool of MIMICS software was used for regularization. According to different gray values of the different-density tissues in the image, the femur and other imaging data were extracted. The self-extraction and erasure filling functions of the software were used to gradually improve the quality of the tissue image. Rough models of bone tissues were obtained and saved as STL files. The STL files were imported into Unigraphics 8.0 (UG)software (Siemens, Munich, Germany) to perform curved surface fitting, fairing processing. Finally, a 3D solid model of the proximal femur will be formed for subsequent processing and finite element model establishment and analysis.

### Acquisition of two types of screw 3D models

In this study, the DhCCS of general care corporation and a commonly used OCCS were selected, and the three-dimensional scanning technology was used for reverse modeling (Fig. 1a) to solve the errors of artificial modeling caused by the complex structure, such as the screw model and screw thread; thus, the results were more realistic.

Model assembly

The femoral neck fracture model (60°, Pauwels type III)[8] was established in UG software. The model assembly was completed according the spatial configurations of the two types of screws, which were implanted in the above model with in an inverted triangle with 2 horizontal and vertical distributions (Fig. 1b). According to the maximum width distribution of the three screws, the upper two screws were parallel to the cortex, and the lower one was close to the femoral moment in the inverted triangle fixation group.[9] In the horizontal fixation group, the anteroposterior images indicated that the screws were anteriorly and posteriorly parallel above the midaxis of the femoral neck, while the lateral images indicated that the screws were near the anterior and posterior cortex of the femoral neck. In the vertical fixation group, the anteroposterior images indicated that the two screws were close to the upper and lower cortex, and the lateral images indicated that they were on the median line.[10] In the same configuration model for the different screws, the screws have a common axis to ensure that they have exactly the same position and length. The model was imported into ANSYS analysis software to provide good preparation for the subsequent biomechanical analysis.

Establishment of the finite element model

In this study, the average size of the proximal femur grid was 3 mm. The mesh was refined around the contact surface between the bone and screw and the fracture block of femoral neck fracture, and the minimum size was controlled above 1.5 mm. Additionally, when establishing the finite element model of the screws, to obtain both the actual structure of the screw and calculation scale of the model at the same time, the average size of the grid was
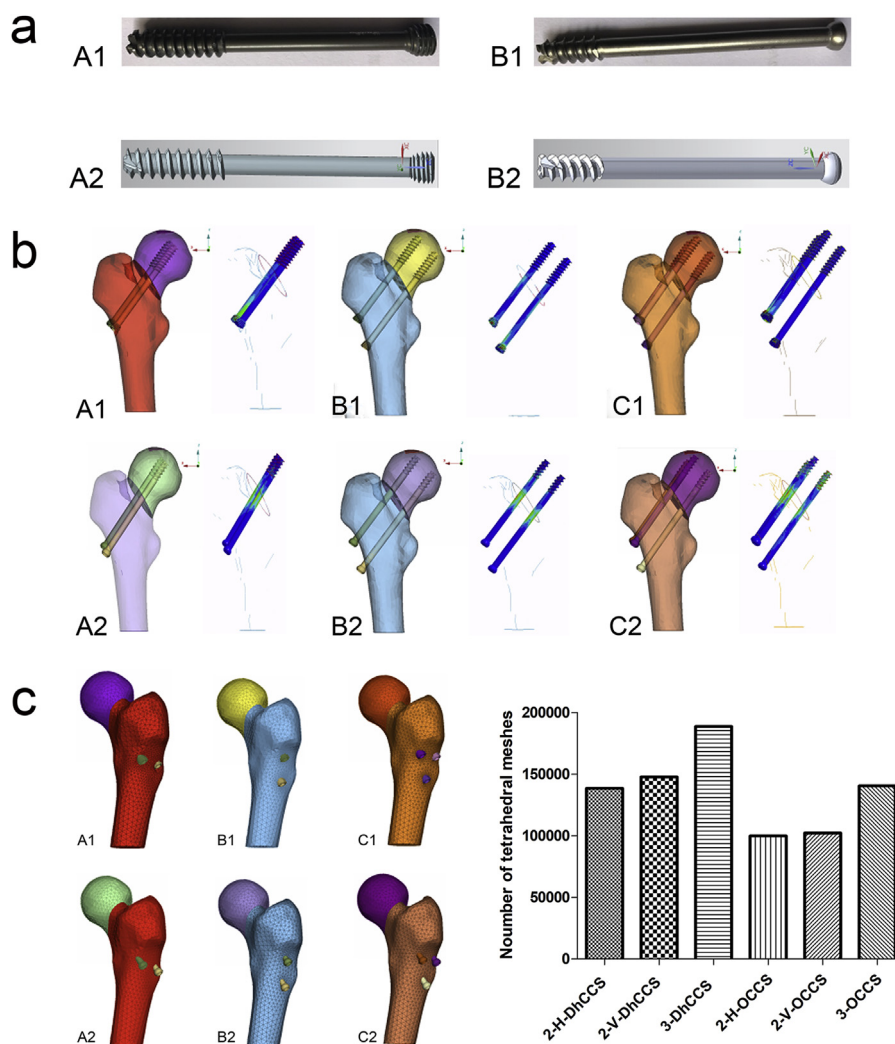
Figure 1 a. Image of two types of screws and screw models after 3-dimensional (3D) scan. A1:The double-head cannulated compression screw (DhCCS) is from general care corporation and has a diameter of 7.3 mm. Both the screw head and tail have a threaded structure; B1: The ordinary cannulated compression screw (OCCS) is the AO screw and has a diameter of 7.3 mm; A2: DhCCS model after 3D scan. B2: OCCS model after 3D scan. b. Assembled model of DhCCS and OCCS fixation of femoral neck fracture (Pauwels 60°). The femoral neck fracture model and position of the screws are well demonstrated. The model of 2-DhCCS horizontal fixation (2-H-DhCCS,A1), 2-DhCCS vertical fixation(2-V-DhCCS,B1), 3-DhCCS (3-DhCCS,C1), 2-OCCS horizontal fixation(2-H-OCCS, A2), 2-OCCS vertical fixation(2-V-OCCS, B2), 3-OCCS inverted triangle fixation (3-OCCS, C2). c. Diagram of the finite element model (FEM) of femoral neck fracture. Different models get appropriate meshes.

1.2 mm, and the minimum control was above 0.6 mm. In the final finite element model of the whole analysis object, the number and scale of the tetrahedral mesh are shown in Table 1, and the completed finite element models are shown in Fig. 1c.

Table 1 Tetrahedral mesh quantity table.

Group	Number of tetrahedral meshes
2-H-DhCCS	138,474
2-V-DhCCS	147,677
3-DhCCS	188,607
2-H-OCCS	99,904
2-V-OCCS	102,126
3-OCCS	140,416

Displacement and stress distribution after loading

The finite element models were imported into ANSYS 17.0 (Inc., Canonsburg, PA, USA) software to assign the displacement and stress distribution. The loading method of this model was fixed at the bottom of femur, and the coupling node at the top of femur head was loaded with a self-weight load. Loading was performed slowly to 600N at the top of the femoral head and was then submitted to LS-DYNA for quasi-static calculation. The model loads and constraints are shown below (Fig. 2a).

Application of cadaver specimen model

In this model study, all 30 cadaver specimens were collected from the department of anatomy, chongqing
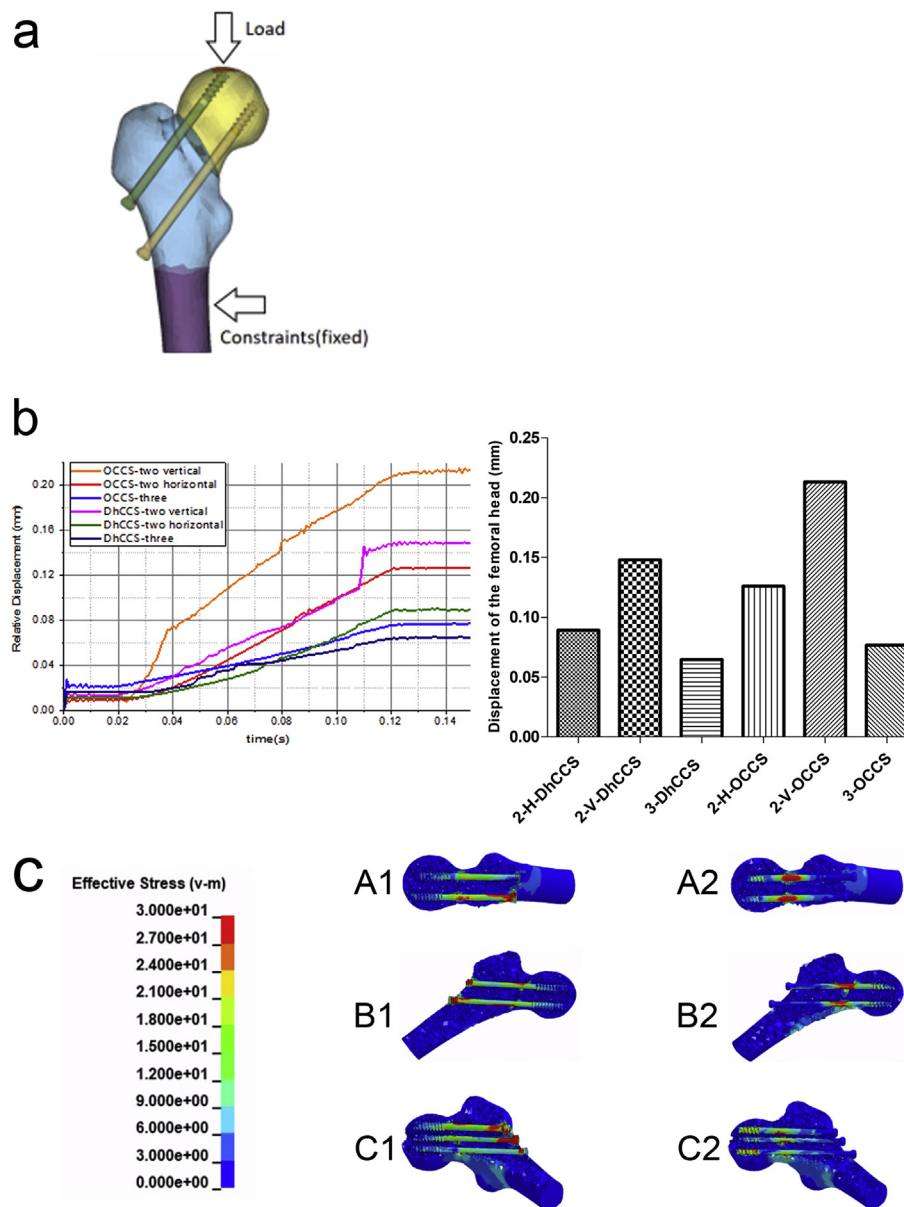
Figure 2 Diagram of finite element analysis. a: Loading diagram, b: Displacement value and change trend (displacement-time) diagram of the femoral head after 600N loading. The bottom curve shown in the figure is the displacement change trend of the 3DhCCS fixation group. The displacement of the femoral head in this group was minimal. The upward order is the 3-OCCS group and 2-H-DhCCS group, and the group with the largest displacement is the 2-V-OCCS group at the top; c: Diagram of stress distribution.

medical university. The research protocol was approved by the ethics committee of chongqing medical university.

The model preparations were shown in Fig. 3a. There were 6 groups with 5 specimens in each group, including two DhCCS horizontal fixation group (A1), two DhCCS vertical fixation group (B1), and three DhCCS inverted triangle fixation group (C1), two OCCS horizontal fixation group (A2), two OCCS vertical fixation group (B2), and three OCCS inverted triangle fixation group (C2).

All specimens were tested by the SANS testing machine (MTS Industry Systems CO.LTD,China)in the mechanics experiment center of chongqing university. As shown in Fig. 3b, the fixed specimen was pasted with resistance strain gauge, and the DH3818 static strain tester (Dong Hua

Test CO.LTD,China)was connected with wires, and the displacement measuring instrument was installed at the femoral head to measure its horizontal displacement. Then, the linear load of 0–600N is loaded at a rate of 1.2 mm/min, and the corresponding readings are showed on the strain gauge and the displacement measuring instrument. Finally, continue and record the load to the specimen until yield.

Statistics analysis

Results were calculated as the mean ± standard deviation (SD). Differences in multiple groups were repeatedly matched and analysed using one-way analysis of variance
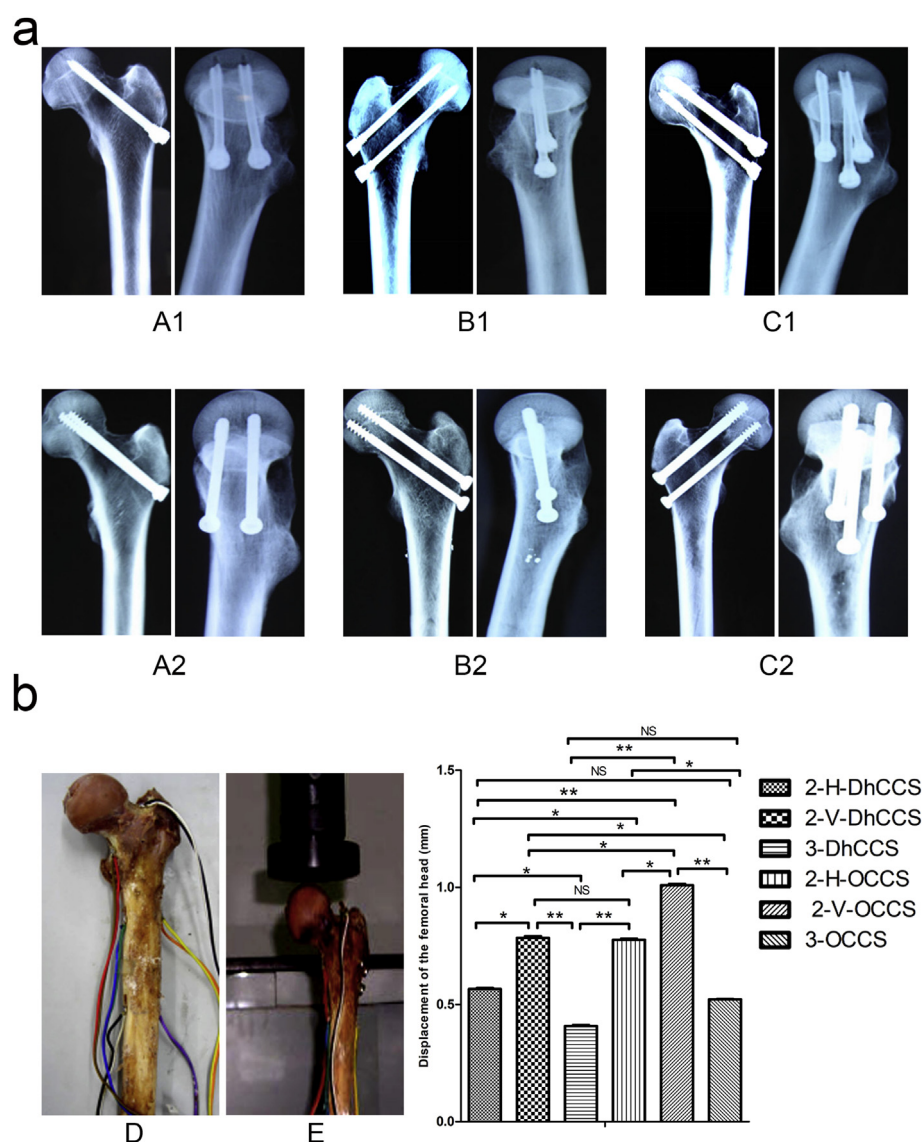
Figure 3 Established cadaver specimen model. a. X-ray images of cadaver specimen models with different groups of screw fixation methods.The model of 2-H-DhCCS(A1), 2-V-DhCCS(B1), 3-DhCCS(C1), 2-H-OCCS(A2), 2-V-OCCS (B2), 3-OCCS(C2). b. Loading diagram of cadaver specimen model, Compared the strain, horizontal displacement of femoral head, yield load and corresponding displacement after 600N loading in each group. *P < 0.05, **P < 0.01, NS: P > 0.05.

(ANOVA) and Tukey's post hoc test using SPSS 22.0 version statistical software. P < 0.05 was regarded as statistically significant.

Results

Displacement

The following was observed according to the displacement value and change trend of the femoral head loading after fixation of the femoral neck fracture model using the two types of spatially distributed screws. The displacement value of the femoral head in the DhCCS group was smaller than that in the OCCS group. The displacement value in the two horizontal groups was smaller than that in the vertical group. The displacement value in the three-screw group was smaller than that in the two-screw group, and the

displacement value in the two-horizontal-DhCCS group was similar to that in the three-OCCS group (Table 2 and Fig. 2b).

Stress distribution

Fig. 2c showed stress distribution in the DhCCS and OCCS groups. Overall, the maximum stress was distributed at the fracture end. The stress distribution in the DhCCS groups was more dispersed than that in the OCCS groups, and part of the stress was transferred to the screw cap at the tail end, resulting in stress dispersion at the fracture end. The stress distribution in the double horizontal screw fixation group was larger in the front screw and smaller in the rear screw. The stress distribution in the vertical groups was concentrated on the upper screw. The stress distribution in the three-screw group was concentrated on

Table 2 Displacement of the femoral head after 600N loading.

Group	Displacement (mm)
2-H-DhCCS	0.0890
2-V-DhCCS	0.1479
3-DhCCS	0.0646
2-H-OCCS	0.1259
2-V-OCCS	0.2131
3-OCCS	0.0767

the two screws on the top, while that of the bottom screw was relatively small.

Test results of cadaver specimens

Table 3 showed the strain, horizontal displacement of femoral head, yield load and corresponding displacement after 600N loading. There were no significant differences in the yield displacement among the 6 groups ($P > 0.05$), and the other indexes had significant differences ($P < 0.05$). Significant differences also existed between group A1 and B1, C1, A2, B2, respectively ($P < 0.05$). Group A1 and C2 had no statistical difference ($P > 0.05$); There were significant differences between group B1 and C1, B2, C2, respectively ($P < 0.05$). No statistical difference existed between group B1 and A2 ($P > 0.05$); There were significant differences between C1 and A2, B2,respectively ($P < 0.05$), No statistical difference was found between group C1 and C2($P > 0.05$); There were significant differences between group A2 and B2, C2, respectively ($P < 0.05$). Group B2 and C2 also had significant difference between ($P < 0.05$).

Discussion

The optimal treatment for femoral neck fractures remains controversial and can be treated using various methods, including by using dynamic hip screws or two or three parallel cannulated compression screws, as well as by joint replacement or nonsurgical treatment for some cases.[11] Particularly, compared with hip replacement, internal fixation for the treatment of femoral neck fractures in the elderly has the advantages of less trauma, less bleeding, and lower mortality, but this method has a high reoperation rate and high cost.[12] CECILIA RO[13] believed that the life quality of elderly patients with displaced femoral neck fractures could be better treated by joint replacement. Early anatomic reduction is mainly advocated for femoral neck fracture, and reasonable and effective internal fixation devices are selected to reduce local blood supply destruction and promote early fracture healing. The quality of the reduction during surgery directly determines the success of internal fixation surgery, and no internal fixator can compensate for the problems caused by poor reduction.[14,15] Femoral neck fractures in young adults (non-elderly) are usually the result of multiple trauma and high-energy injuries, and the treatment emphasizes accurate reduction and stable fixation.[16-18] Gozna[19] believed that internal fixation of femoral neck fracture must meet the following conditions: resistance to shear stress applied to the fracture line, resistance to bending stress and allowable axial compressive stress. In clinical practice, various internal fixation options exist for the treatment of femoral neck fracture. However, presently, the pure titanium cannulated compression screw recommended by the international society of internal fixation (AO/ASIF) remains widely used in the clinical treatment of femoral neck fractures. It has some advantages, such as a simple surgical procedure, less local anatomical separation, and shorter operation time. Titanium metal also has good histocompatibility and stability and is not prone to loosening and infection. Its advantages have been accepted by most scholars, Additionally, the use of cannulated compression screws with inverted triangle fixation is well recognized biomechanically as a better option, and this approach is the most commonly used surgical method. However, the following problems are often encountered in clinical practice: (1) When the femoral neck is relatively small and the fracture is shattered, it is difficult to implant the third screw, and the third screw can easily penetrate the femoral neck cortex. (2) Femoral neck shortening easily occurs in the fixation with OCCS, and the phenomenon of screw withdrawal easily occurs in the case of osteoporosis. Clinically, there is a controversy over whether to choose OCCS or DhCCS. (3) It is controversial whether two screws can be used to replace three screws in clinical practice. (4) Further, the method for selecting the spatial configuration

Table 3 Biomechanical index test results of 600N load in each group.

Index	A1	B1	C 1	A2	B2	C2	P value
$\varepsilon 1$	897 ± 89	1563 ± 153	824 ± 120	999 ± 105	1853 ± 299	941 ± 89	<0.05
$\varepsilon 2$	794 ± 302	1184 ± 79	624 ± 75	871 ± 122	1383 ± 297	699 ± 118	<0.05
$\varepsilon 3$	436 ± 168	958 ± 62	356 ± 51	496 ± 37	963 ± 472	389 ± 65	<0.05
$\varepsilon 4$	662 ± 192	1164 ± 244	557 ± 84	881 ± 93	1504 ± 727	592 ± 51	<0.05
$\varepsilon 5$	534 ± 104	824 ± 102	448 ± 49	606 ± 108	847 ± 254	453 ± 132	<0.05
$\varepsilon 6$	361 ± 81	705 ± 138	221 ± 94	406 ± 62	645 ± 344	197 ± 89	<0.05
Displacement (mm)	0.569 ± 0.18	0.786 ± 0.97	0.409 ± 0.11	0.774 ± 0.27	1.007 ± 0.15	0.522 ± 0.27	<0.05
Yield load(N)	2129 ± 150	1654 ± 336	2229 ± 424	1666 ± 100	1246 ± 162	2201 ± 509	<0.05
Yield displacement (mm)	4.987 ± 0.80	5.334 ± 0.56	4.918 ± 0.54	5.350 ± 0.34	5.476 ± 1.34	5.028 ± 0.89	>0.05

($\varepsilon 1$, $\varepsilon 2$, $\varepsilon 3$ represent the strain values from the top to the bottom of proximal medial femur, $\varepsilon 4$, $\varepsilon 5$ and $\varepsilon 6$ represent the strain values from the top to the bottom of proximal lateral femur.).

of two screws for fixation of femoral neck fractures is controversial.

To solve these problems, the biomechanical effects of DhCCS and OCCS for the treatment of femoral neck fractures were analyzed by the computer finite element method. Finite element analysis is a theoretical method of biomechanical research, which can simulate the geometric models of various structures, endows various tissues with biological material properties, and can well reflect the general trend of its biomechanical properties. Therefore, it can be a good supplement for the research methods of specimen experimental biomechanics. This study had the following characteristics. First, two screw models consistent with the screw entity were obtained by 3D scanning technology in this study. MIMICS software was used to construct the 3D solid model of the proximal femur by CT scan, and UG software was used to establish assembly model of femoral neck fracture and screws; then, ANSYS software was used to carry out finite element analysis. Second, this study is the first to compare finite element analysis of femoral neck fracture fixation using DhCCS and OCCS; It plays a guiding role in the selection of screws in clinical practice. Third, the displacement trend obtained by finite element analysis was consistent with the cadaver specimen test results, indicating the validity and practicability of this model.

The following conclusions can be drawn from the experimental results. (1) The fixation stability of DhCCS is better than that of OCCS. The reason is that it has a tail thread design, which can press the fracture ends together better and can enhance the pressure force at the fracture end to better resist the shear and bending force. (2) The biomechanical stability of horizontal fixation with 2 screws was better than that of vertical fixation. Because the normal femoral neck stress distribution includes lateral tensile stress and medial compressive stress, when the femoral neck is fractured, the fracture end cannot resist lateral tensile stress, but the internal femoral neck can still be in close contact through the bone fracture end to resist certain compressive stress; thus, it is more important to enhance resistance to lateral tensile stress. The two screws were fixed above the central shaft of the femoral neck in the anterior and posterior parallel, producing better resistance abilities to shear stress, tensile stress and bending stress on the tensile side than the two screws in the vertical position; thus, the fracture end had a better compressive stability effect, which was consistent with the experimental results of Tan V.[10] (3) The biomechanical stability of 2 horizontal DhCCS fixation showed no obvious difference with three OCCSs; this result was observed mainly because the two screws are on the tension side of the femoral neck either in two-DhCCS or three-OCCS fixation, according to the biomechanical characteristics of the femoral neck. The result is consistent with the results of Walker.[20] According to Maurer,[21] fixation of femoral neck fracture with two screws is acceptable and can reduce the cost of implantation by 1/3 and can decrease the time of surgery and incidence of intraoperative complications; however, the fixation strength can be increased when the third screw is implanted. Through case review analysis, Xarchas[22] concluded that fixation to treat femoral neck fracture with two screws is sufficient to provide mechanical

strength, a short operation time and less trauma, which can reduce the destruction of the local blood supply of femoral neck and facilitate fracture healing. (4) There was no significant difference between the three-screw groups. Fixation of femoral neck fractures using three screws with 2 different structures in the inverted triangle position showed good mechanical stability, which was consistent with the biomechanical research results of mainstream scholars. (5) The 2 vertical OCCS group had the worst effect in this study.

Because the tail end of the DhCCS had a thread design, it showed a better stabilizing effect of compression on the fracture end in the treatment of femoral neck fracture. Additionally, because the 2 DhCCSs in the horizontal position were located on the tension side of the femoral neck, they were in line with the stress distribution law of the femoral neck and had good mechanical stability. In comminuted fractures or unstable fractures, due to the lack of support at the end of fracture, the fractures are fixed with OCCSs because only the head end has a thread, and the sliding compression effect can occur similar to the screw tail becoming loose. However, the adverse effect of sliding compression is shortening of the femoral neck. Zlowodzki[23] showed that femoral neck shortening >5 mm would have a great impact on the hip joint function of patients, while approximately 60% of patients with femoral neck fractures fixed with OCCSs had femoral neck shortening greater than 5 mm within 5 years after surgery. To reduce the problem of shortening in the process of femoral neck fracture healing, some scholars[24] use a full-thread cannulated screw combined with a common compression cannulated screw to treat femoral neck fracture, significantly reducing the femoral neck shortening rate. Because the DhCCS has two end threads, the compression effect is stronger than that of OCCS. Generally, loose screws do not occur, and the second sliding compression does not exist. Clinically, it was found that, because of the double-end thread design of DhCCS, the fracture end could not form the second sliding compression effect when the fracture end failed to heal in the first stage, and the fracture end did not heal well. Therefore, DhCCS is more suitable for noncomminuted and stable femoral neck fractures to obtain the first-stage healing of fractures. This can be well illustrated by the displacement of the DhCCS fixation group being smaller than that of the OCCS in this study.

Conclusions

DhCCS has better biomechanical stability than OCCS. Clinically, DhCCS can be used to treat femoral neck fractures. If the femoral neck is small, a nondisplaced or slightly displaced fracture may be selected treated with two horizontal fixations.

Author contributions

Hui Lu: Study design, biomechanical testing, data analysis, manuscript preparation.

Hongquan Shen: Study design, biomechanical testing, data analysis, manuscript preparation.

Shuqing Zhou: Study design, biomechanical testing, data analysis, manuscript preparation.

Weidong Ni: Study design, biomechanical testing, data analysis, manuscript preparation.

Dianming Jiang: Study design, biomechanical testing, data analysis, manuscript preparation.

All authors have read and approved the final submitted manuscript.

Limitations of this study

This study only compared the biomechanical strength of two types of screws commonly used clinically and ignored the influence of screw thread structure of each.

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Conflict of interest

None.

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