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Finite Element Analysis of Femoral Neck Fracture Treated with Bidirectional Compression-Limited Sliding Screw

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Data Collection B
Statistical Analysis C
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Manuscript Preparation E
Literature Search F
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Background: The rate of femoral neck shortening after internal fixation for femoral neck fracture is high and this complication reduces the function of the affected lower limb. The aim of this study was to design a bidirectional compression-limited sliding screw (BCLSC) that can achieve a full balance between retaining the sliding pressure of the ends of and maintaining the length of the femoral neck.

Material/Methods: We constructed a 3-dimensional model of a Pauwels III femoral neck fracture and models of 3 internal fixation methods (3 cannulated screws [3CS], dynamic hip screw [DHS]+CS, and BCLSC) by finite element analysis (FEA). The finite element model simulated the loading of the human body when standing on 1 leg. Displacement and stress distribution of the models were calculated based on an axial stress of 600 N.

Results: The peak von Mises stress (VMS) values of fracture ends in the 3CS, DHS+CS and BCLSC groups were 94.687 MPa, 26.375 MPa and 45.698 MPa; the peak VMS values of internal fixed stress were 451.53 MPa, 174.45 MPa, and 337.34 MPa; the peak VMS values of the lateral femoral wall were 70.021 MPa, 53.033 MPa, and 20.009 MPa; maximum displacements of the femoral head were 1.4482 mm, 1.3813 mm, and 1.3889 mm; and the internal fixed displacement peaks were 4.1134 mm, 3.91 mm, and 4.1004 mm, respectively.

Conclusions: The FEA showed that compared with the CS, the new BCLSC showed better performance in resisting shearing force for Pauwels III femoral neck fracture, with better mechanical properties. These data provide a basis for further experiments and clinical application.

Keywords: **Bone Screws • Femoral Neck Fractures • Finite Element Analysis**

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Background

The fracture of the femur is a common type of hip fracture, which can occur at all ages and is a health problem affecting people worldwide. Approximately 1.7 million patients have a femoral neck fracture every year worldwide, and these numbers can increase with a growing aging society. By 2050, the number of patients with femoral neck fracture is estimated to be 6.7 million annually [1]. Due to the characteristics of the proximal femoral anatomical structure and biomechanics and the femoral head blood supply, complications often occur after the internal fixation of femoral neck fracture, such as nonunion and femoral head necrosis. It is very difficult to identify ways to improve the internal fixation success rate in orthopedic trauma treatment [2,3].

Recently, with the improved understanding of the femoral head blood supply, the success rate of the internal fixation of femoral neck fractures has improved. However, with the general improvement in patient quality of life, the problem of postoperative femoral neck shortening has attracted more attention. Owing to the anatomical biomechanics of the femoral neck and the healing characteristics of femoral neck fracture, femoral neck shortening is common after femoral neck fracture surgery, and the incidence of shortening has been reported to occur in 27% to 66% of cases [4-8]. Excessive shortening after femoral neck surgery can reduce lower limb gait function and even cause hip joint dysfunction, especially for patients with osteoporosis, which greatly reduces patient quality of life.

In accordance with the anatomical biomechanics of the femoral neck and the healing characteristics of femoral neck fracture and to promote fracture healing and reduce the incidence of postoperative shortening of the femoral neck, we designed a double-threaded compression-limiting sliding screw. First, the screw has a double-thread compression fixation. The inner core and outer sleeve of the screw have a "hexagonal" chimeric structure, which has the characteristics of coaxial movement. In the process of inserting the inner core, the outer sleeve can be placed at the same time. In the design, the screw head and the screw tail have threads, and the screw pitch at the end of the screw is less than the screw pitch of the screw head. Because the screw head and the end of the screw were limited by the thread, the tail side of the screw could not exit from the lateral bone cortex. Second, the design of the screw imitated the principle of a sliding compression plate. The outer sleeve of the screw tail was fixed into the lateral cortical bone of the femur, so that the inner core of the screw could be limited by sliding in the sleeve. The limited sliding process of the screw promoted fracture healing and helped to avoid excessive shortening of the femoral neck (**Figure 1**).

Figure 1. (**A, B**) Design of a new type of sliding screw with bidirectional compression limits for the femoral neck.

To confirm whether the modular structure design of the new bidirectional compression-limited sliding screw (BCLSC) provided adequate stability, we analyzed the von Mises stress (VMS) and displacement of the new screw system and compared it with the 2 traditional methods (3 cannulated screws [3CS] and a dynamic hip screw [DHS]+CS) of repairing Pauwels type III femoral neck fracture by finite element analysis (FEA).We further evaluated the mechanical stability of the new BCLSC, and provided a theoretical basis for its clinical application.

Material and Methods

The 3-Dimensional Model of Femoral Neck Fracture and Internal Fixation

We recruited a healthy 30-year-old man with a body weight of 60 kg as a volunteer participant. The existence of hip injury and disease were excluded by a physician. The left femur was scanned layer by layer using a spiral computed tomography (CT) scanner (Toshiba 64-row 128-slice CT scanner; Toshiba, Tokyo, Japan), and the raw data were collected in DICOM format. After inputting the raw data into Mimics21.0 software (Materialise, Leuven, Belgium), the 3-dimensional (3D) model was preliminarily established by image segmentation, delineation, and edge smoothness, and the model data file was outputted in STL format. The STL format file generated by Mimics was inputted into Geomagic software (3DSystems Inc, Rock Hill, SC, USA) for smoothing, editing contour lines, surface generation, and surface fitting, and then the file was outputted in common STP geometry model format. Finally, we

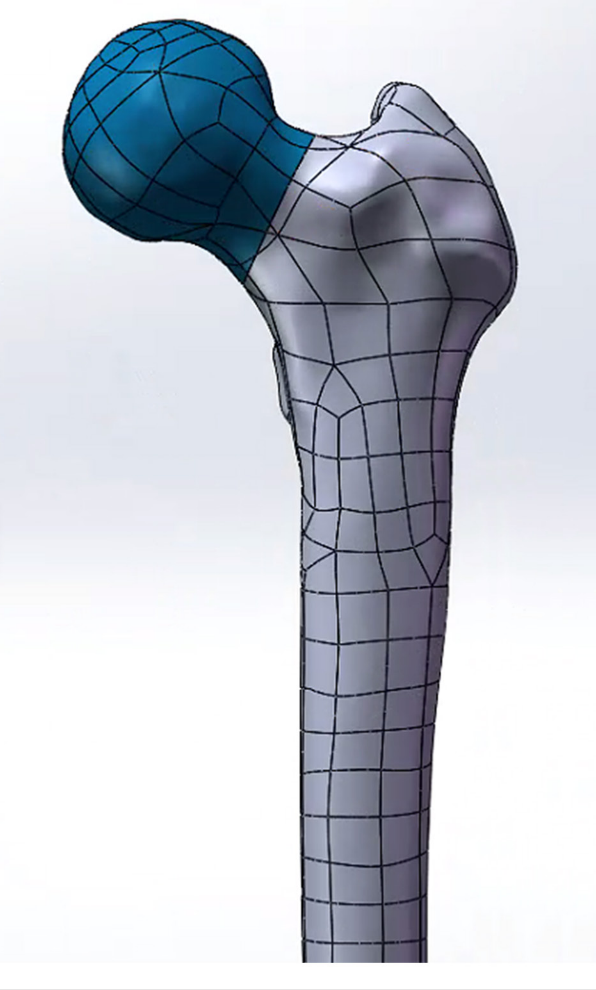

Figure 2. Femoral neck fracture; Pauwels type III fracture.

inputted the STP geometric model format file into SolidWorks software (Dassault Systemes, Vélizy-Villacoublay, France) for solid reconstruction, and a Pauwels III fracture was created in the 3D model (Pauwels Angle >70°; **Figure 2**). The feature/surface module in SolidWorks software was used for modeling various types of internal fixation (CS with thread diameter 7.3 mm, DHS system, BCLSC), and the model was saved in SLDPRT format. Next, the different types of screws were assembled into the bone. Finally, we obtained 3 fracture internal fixation 3D models by using the combination process overlapping part of the intersection (**Figure 3**).

Finite Element Model Analysis

The model generated in SolidWorks was input into Ansys software (Ansys, Canonsburg, PA, USA), and the material property parameters of cortical bone, cancellous bone, and internal fixation were calculated [9, 10]. Different contact surfaces were defined with different contact relations as follows: The fracture surface was set to friction (friction coefficient=0.24). Frictional contact was used between the screw and sleeve (friction coefficient=0.2), The threaded screw area was used for binding to the bone, and the non-threaded area remained frictional contact with the bone (friction coefficient=0.24).

Finally, the model was meshed. To ensure that the calculation accuracy met the requirements of analysis, the mesh type and mesh size were controlled, with the mesh type set as a hexahedral mesh, and the mesh size set as 1.5 mm (**Table 1**).

Boundary Conditions and Loads

A simplified bone model was created, and the force of the acetabular fossae on the femoral head was mainly used to simulate the force of the unilateral femur during walking (close to the midpoint data of the normal human walking cycle). Six degrees of freedom were fixed on the bone surface of the distal femur, and a 600 N load was applied vertically down from the femoral head [11,12] (**Figure 4**).

Evaluation Index

To evaluate the different internal fixation methods for femoral neck fractures under mechanical loading conditions, we needed to focus on the following variables: (1) VMS peak and distribution of fracture broken ends; (2) VMS peak and distribution of internal fixation; (3) VMS peak and distribution on the lateral wall of the femur; (4) displacement distribution and peak value of the femoral head and internal fixation; and (5) displacement distribution and peak value, and VMS distribution and peak value of the inside of the new screw type.

Results

VMS Distribution at Fracture Ends

The stress distribution at the femoral neck section showed that the stress peaks of all models were concentrated in the contact region of the medial femur with the internal fixation and the proximal medial femur near the lesser trochanter. The peak stress of fracture end of the 3CS group was 94.687 MPa, and that of the DHS+CS group was 26.375 MPa. Compared with the stress peak of the 3CS group, that of the BCLSC group was significantly lower at 45.698 MPa (**Figure 5, Table 2**).

VMS Distribution and Peak Values of Internal Fixation

Stress distribution maps of the internal fixation methods showed that the stress of internal fixation was concentrated in 3 areas: where the head and tail of the screw contacted the bone, in the screw itself, and at the broken end of the bone. The peak stress was 451.53 MPa in the 3CS group, 174.45 MPa

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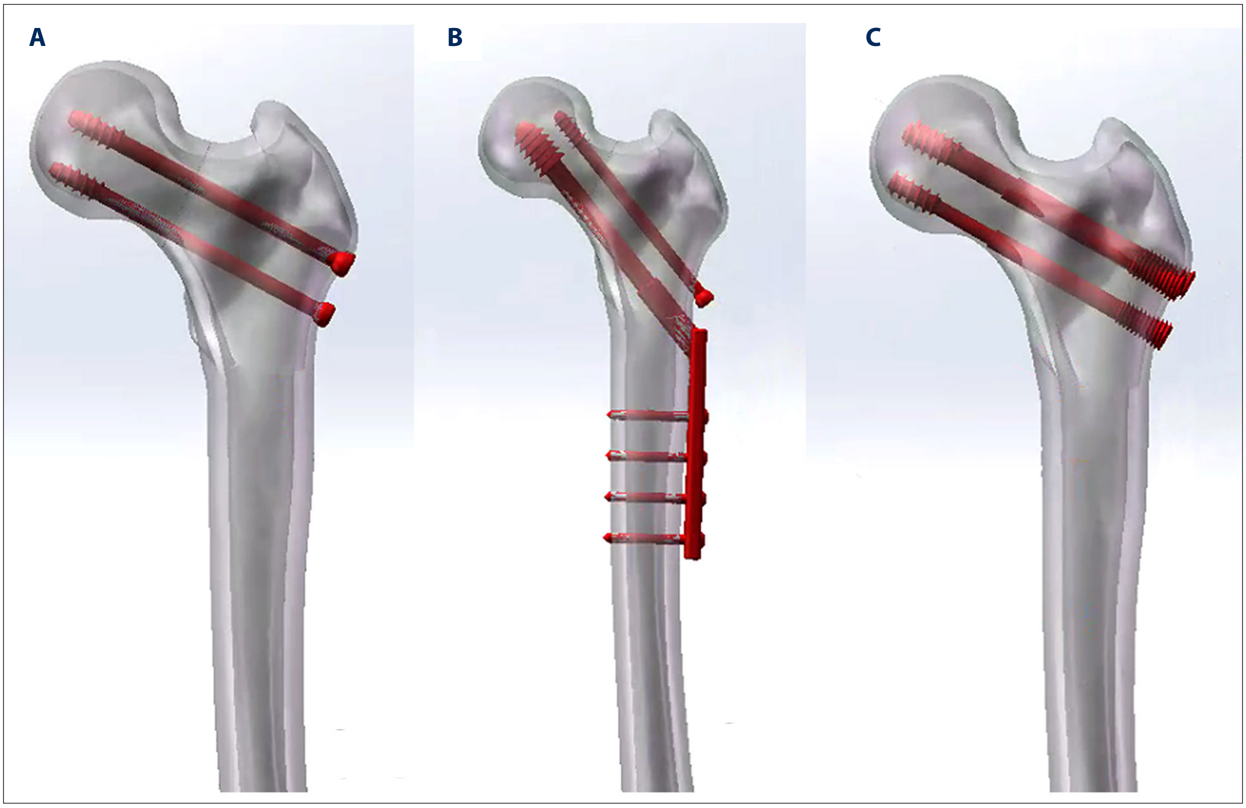

Figure 3. Model of a femoral neck fracture treated with internal fixation in the 3 groups: (**A**) 3 cannulated screws (3CS); (**B**) dynamic hip screw and cannulated screw (DHS+CS); (**C**) bidirectional compression-limited sliding screw (BCLSC).

Table 1. Number of nodes and elements of the finite element model.

FE models	Node number	Number of units
3CS	969,208	644,290
DHS+CS	1,140,569	757,438
New type of screw	1,070,655	690,135

in the DHS+CS group, and 337.34 MPa in the BCLSC group. In the 3CS and BCLSC groups, the stress peak of the posterior upper distributed screw was the highest.

Stress Distribution and Peak Values at the Lateral Femoral Wall

According to the map of stress distribution at the femoral lateral wall, the stress peak value in the 3CS group was 70.021 MPa and was concentrated in the area where the distal screw was in contact with bone. In the DHS+CS group, the stress peak was 53.033 MPa, concentrated in the area where the proximal screw contacted the bone. The BCLSC group had no obvious stress concentration, and its stress peak value was only 20.009 MPa.

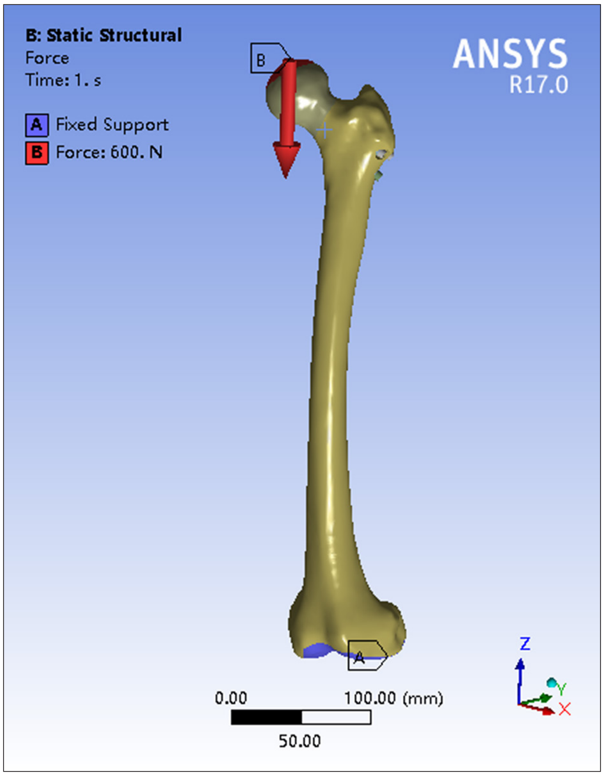

Figure 4. Schematic diagram of mechanical loading.

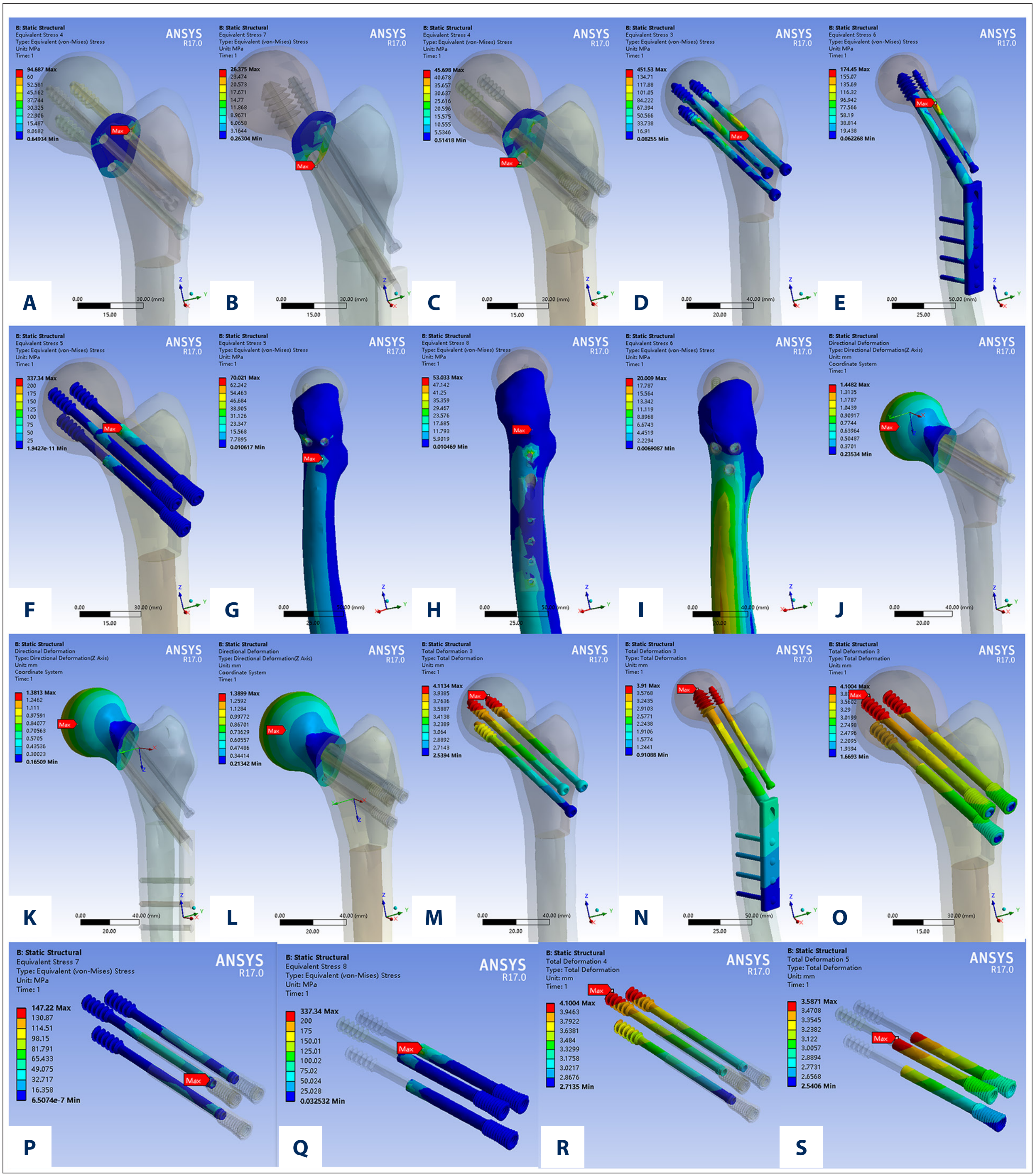

Figure 5. Finite element stress and displacement map of the model. (**A-C**) Stress distribution map of the fractured bone ends of the finite element model; (**D-F**) Map of internal fixed stress distribution in the finite element model; (**G-I**) Map of stress distribution on the lateral femoral wall of the finite element model; (**J-L**) Distribution map of femoral head displacement in the finite element model; (**M-O**) Map of internal fixed displacement distribution in the finite element model; (**P-Q**) Map of stress distribution in the internal structure of the bidirectional compression-limited sliding screw (BCLSC); (**R-S**) Map of displacement distribution of internal structure of the BCLSC.

Table 2. Results of maximum stress and displacement of the finite element model of the different groups.

Groups	Fracture stress (MPa)	Lateral femoral wall stress (MPa)	Internal fixed stress (MPa)	Femoral head displacement (mm)	Internal fixed displacement (mm)
3CS	94.687	70.021	451.53	1.4482	4.1134
DHS+CS	26.375	53.033	174.45	1.3813	3.91
New screw	45.698	20.009	337.34	1.3899	4.1004

Femoral Head and Internal Fixation Displacement Peak and Distribution

Due to axial force on the neck of the femur, the femoral head sunk and shifted downward. Displacement maps of the femoral head and internal fixation showed that the displacement of the femoral head in the 3 groups was as follows: the maximum displacements of the femoral head were 1.4482 mm, 1.3813 mm, and 1.3889 mm in the 3CS, DHS+CS, and BCLSC groups, respectively. The displacement direction was the same on the internal fixator and the femur. The internal fixator displacement of the 3 groups was concentrated on the screw head under the femoral head and was decreased from the head to the tail of the screw. The maximum internal fixation displacement values of different groups were 4.1134 mm, 3.91 mm, and 4.1004 mm in the 3CS, DHS+CS, and BCLSC groups, respectively. In the 3CS and BCLSC groups, the displacement peak values were largest at the head of the screw on the upper screws.

Displacement and Stress Distribution of the BCLSC

The stress distribution of the BCLSC showed that the stress of the inner core was concentrated at the junction of the tail end and the outercoat and was distributed evenly and gradually toward the proximal screw end. However, the stress peak of the outercoat was concentrated at the junction of the outercoat head and the inner core. The displacement peaks of the inner core and the outercoat were located at the proximal screw end.

Discussion

Using FEA in this study, we compared the biomechanical stability of the newly designed BCLSC screw with that of the 3CS and DHS+CS methods in the fixation of Pauwels type III femoral neck fractures. Displacement maps of internal fixation and the femoral head showed that, compared with the 3CS group, the BCLSC group had a greater anti-shear force effect. The stress distribution of fracture end and internal fixation showed that the stress peak value in the BCLSC group was significantly lower than that in the 3CS group, which could stabilize fractures, indicating the new BCLSC screw had a lower risk of internal fixation failure for femoral neck fracture. The incidence of subtrochanteric fracture in the BCLSC group was lower than that of the 3CS group. The stress of the lateral wall of the femur of the BCLSC group was significantly lower than that of the 3CS group, which led to a lower incidence of subtrochanteric fracture.

The aim of internal fixation for a femoral neck fracture is to provide a stable biomechanical environment for fracture healing by resisting shear stress and simultaneously maintaining axial compressive stress of the femoral neck. In the present study, the sliding compression of fracture ends was beneficial to fracture healing. There is still controversy regarding the selection of internal fixators [13,14]. At present, CS and DHS are the most widely used devices in the treatment of femoral neck fractures, having the advantages of simple operation and sliding pressure, while the combination of DHS+CS significantly improves the anti-shearing and anti-rotation effects. In a study of biomechanics, Stoffel et al [15] used cadaveric specimens to study the biomechanics of Pauwels type III femoral neck fractures treated with internal fixation, and the results showed that the axial stiffness of their DHS+CS group was 688±132.6 N/mm, which was significantly greater than the axial stiffness of the 3CS group, which was 584.1±156.6 N/mm. In biomechanical experiments conducted in vitro by Samsami et al [12], the axial stiffness of the DHS+CS group was 404.3 N/mm, while that of the 3CS group was 243.1 N/mm. Using FEA, Li et al [16] compared the use of CS with DHS+CS in Pauwels type III fracture fixation. By performing FEA after simulating standing on 1 leg and loading 2100 N vertically down onto the femoral head, their results showed that the maximum displacement of the femoral head in the CS and DHS+CS groups was 8.1479 mm and 8.0087 mm, respectively. The maximum displacement of internal fixation was 7.9592 mm and 7.3649 mm in the CS and DHS+CS groups, respectively, at the screw head, and the maximum rotation angle was 2.35° and 1.88°, respectively. Our present study of the finite elements suggested that DHS+CS fixation offered more effective stability than did 3CS in the fixation of a Pauwels type III femoral neck fracture. This result is consistent with the previous biomechanical and finite element studies, which shows the validity of this present study.

CS and DHS are sliding and pressurizing systems, and femoral neck shortening is common after surgery [4,7]. Neck shortening after surgery for femoral neck fracture will lead to hip joint dysfunction due to femoral neck eccentricity, abduction muscle weakness, and reductions in speed, symmetry, and physical function of gait [5,17]. Femoral neck shortening leads to dislocation of the screw end, causing pain and affecting patient quality of life. Excessive shortening is associated with necrosis of the femoral head. Many studies of biomechanics and finite element experiments have indicated that the DHS+CS system provides great stability for femoral neck fracture. However, a higher incidence of femoral head necrosis is associated with the use of DHS+CS. The large dynamic screw of DHS has a strong sliding compression effect and can provide good stability for the fracture end. However, comminution at the fracture end will cause significant femoral neck shortening, and the fracture end will continue to move slightly, which can lead to later femoral head necrosis [5]. In 2017, the Lancet published an international, multicentric, prospective study on the selection of internal fixation for femoral neck fractures [18]. Among 1108 patients with femoral neck fracture for internal fixation, 557 patients were fixed with DHS and 551 with CS. The patients were followed for more than 24 months, and the authors found that there was a high rate of femoral neck shortening (>5 mm) after surgery in the DHS (26%) and CS (29%) groups. Further studies later found that femoral neck shortening reduces hip joint function [8].

Here, we designed the BCLSC that can achieve a full balance between retaining the sliding pressure of the ends of and maintaining the length of the femoral neck. From this FEA study, we found that the new type of screw has better biomechanical properties, lower risk of fracture of femur and screw, and is more conducive to fracture healing. The structural and mechanical characteristics of the BCLSC have advantages for use in for femoral neck fractures. First, the inner core and outer sleeve of the screw are a "hexagonal" chimeric structure, which has the characteristics of coaxial movement. In the process of inserting the inner core, the outer sleeve could be inserted simultaneously. The screw head and the screw tail have threads, and the screw pitch at the end of the screw is less than that of the screw pitch of the screw head. When the screw tail thread was screwed into the femur, the fracture end could be pressurized again, and the compression effect and friction of the fracture end were enhanced. This may be confirmed by in vitro biomechanical experiments. Second, the internal core of the screw can slide in the outer sleeve, and the sliding distance can be limited within the allowable range by local clamping to promote fracture healing and avoid excessive shortening of the femoral neck. Furthermore, because the inner core and outer sleeve together form a sliding combination, this could improve the stress distribution of the screw, the fracture end, and the lateral wall of the femur, which was consistent with the present experimental results. The stress between the fracture end and the lateral wall of the femur decreased significantly compared with CS and theoretically could reduce the complications of internal fixation failure.

Limitations

This study has some limitations. First, data analyses of the joint capsule, ligament, and periosteum were not included. Second, only a single perpendicular stress to the femoral head was applied, which did not replicate the complex stress under the normal physiological conditions; therefore, the experimental results will be somewhat different from actual clinical conditions. Further biomechanical experiments are needed to verify the results. Third, in this study, only the inverted triangle fixation was compared, and the different combination of screws was ignored. Finally, this study was limited to the observation of immediate stability after fracture fixation, and could not completely simulate the biomechanical process of fracture healing. Thus, further clinical trials and observations need to be performed.

Conclusions

In this study, the FEA results showed that compared with the CS, the new BCLSC showed a better performance in resisting shearing force for Pauwels type III femoral neck fracture, with better mechanical properties. These data provide a basis for further experiments and clinical application.

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Conflicts of Interest

None.

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