

Finite element analysis of spiral plate and Herbert screw fixation for treatment of midshaft clavicle fractures

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Abstract

Both spiral plate and Herbert screw fixations have been clinically adopted for treating midshaft displaced clavicle fractures. However, the biomechanical properties of the 2 implant fixations have not yet been thoroughly evaluated. Here we report the results of a finite element analysis of the biomechanical properties of midshaft clavicle fractures treated with Herbert screw and spiral plate fixation. Herbert screw fixation showed stress distribution similar to intact clavicle under all loading conditions, but provided less stability than did spiral plate fixation. Postoperatively, excessive shoulder activities and weight-bearing should be avoided. Spiral plate fixation provides greater stability, but is associated with stress shielding. These results demonstrate that Herbert screw fixation is suitable for the treatment of simple displaced clavicular fractures, but excessive shoulder activity and weight-bearing should be avoided after the operation. Therefore, spiral plate fixation may be preferred for patients requiring an early return to activity.

Abbreviations: CT = computed tomography, FE = finite element, INP = Input, Mpa = Megapascal, N = Newton, Nm = Newton-meter, STEP = standard for the exchange of product model data, STL = stereolithography.

Keywords: biomechanics, clavicle fracture, finite element, herbert screw, spiral plate

1. Introduction

Clavicle fractures are common among young, active individuals and mainly result from traffic accidents, sports injuries, or falls.^[1] Approximately, 80% to 83.7% of clavicle fractures involve the midshaft, and over half of these fractures are displaced because of the relatively narrow cross-section of the bone experiencing excessive torsional or bending stress.^[1–4] Historically, midshaft clavicular fractures treated nonsurgically were deemed to have a

good prognosis. However, more studies on fracture mechanisms and clinical complications suggest that nonsurgical treatment of clavicular fractures may be associated with excessive pain and discomfort. Clavicle fracture shortening, displacement, and comminution occurring as a result of nonoperative management can produce persistent discomfort and are associated with poor functional outcome.^[5] As a result, open reduction internal fixation of midshaft clavicle fractures, through use of a plate or intramedullary device, has become a common treatment approach.^[2,6]

Plate fixation, by multifarious techniques, of midshaft clavicular fractures is considered the criterion standard, as it provides sufficient fixation, stabilization, and early mobility.^[7] Fixation can be applied to anterior plate, superior plate, or spiral plate. Several studies have shown that spiral clavicle plate treatment resulted in less skin irritation and better multidirectional and stable biomechanical properties than treating superior or anterior plate.^[8–10] Plate fixation has also been shown to present risks of stress shielding at the fracture site, re-fracture following implant removal, and hypertrophic callus formation, while also requiring greater exposure and significant soft tissue stripping leading to reduced blood supply and interference with bone healing.

These problems have spurred more research focused on intramedullary fixation approaches, which require less skin dissection and result in less cosmetic damage.^[11–13] The Herbert screw is a cannulated, headless, double-threaded screw that imparts rapid compression to promote bone healing.^[2,14] Previous studies have shown that Herbert screw utilization results in good clinical and functional outcomes and is an effective surgical treatment of midshaft clavicular fractures.^[14,15] However, biomechanical stability under physiological conditions has not been extensively investigated, particularly in comparison to plate fixation.

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XZ and XC contributed equally to this work.

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The 3-dimensional finite element (FE) method can accurately simulate human skeleton anatomical structures and internal fixation devices. It is often used to quantitatively assess stress distribution and microdeformation of bone/implants and is useful for optimizing the design of orthopedic implants.^[16–19] It is emerging as a powerful computational tool in the field of orthopaedics.

Here, we have used FE to evaluate implant stresses and micro-motions, comparing Herbert screw and spiral plate treatments for midshaft clavicular fractures. The conclusions provide a biomechanically based framework in which to consider the application of one or the other approach.

2. Methods

2.1. Image data collection and bone modeling

A computed tomography (CT) scan of the right, healthy clavicle of a female volunteer (age: 22 years; weight: 51 kg; height: 164 cm) was used to generate the clavicle model. The volunteer's medical history excluded infectious diseases, skeletal disorders, osteoporosis, metabolic bone disease, hormonal imbalance and cancer. The volunteer had normal bone mass, based upon values estimated from quantitative computed tomography data.

Slice thickness of CT images was 0.75 mm (512 × 512 pixels per image). Digital Imaging and Communications in Medicine data were imported into Mimics 17.0 software (Materialise, Belgium) for thresholding and region growing. The cortical shell and the inner spongy bone of the clavicle were created based on the Hounsfield values of the bone.^[20] Subsequently, a stereolithography (STL) file of the clavicle model was smoothed and materialized in the Geomagic Studio 2013 software (3D System Inc., Rock Hill, SC). A standard for the exchange of product model data (STEP) of the clavicle was then imported into the NX 9.0 (NX Generation, Siemens, Germany) software for simulating the spiral plate fixation and Herbert screw fixation models. A 4-mm transverse fracture gap, having an angle <30 degree and devoid of overlapping triangles, was simulated between the fractured segments of the middle-shaft of the clavicle.^[8,21] The plate and screws were oriented and positioned according to the manufacturers' specifications.

The 7-hole spiral locking plate and 3.5-mm-diameter solid cylinders of the screws were modeled (Naton, China). The curvatures of the spiral locking plate were adjusted to conform to the path of the clavicle. A 3.5-mm-diameter locking screw was placed into each of 6 screw holes (excluding the center screw hole) in the spiral plate model. All screws were set perpendicular to the plate using bicortical locked plating.^[22] The Herbert screw was 85 mm in length and 4.5 mm in diameter, and was positioned across the fracture gap according to manufacturer recommendations (Zimmer, China).

2.2. FE modeling

The STEP files of the models were entered into HyperMesh (Altair) software for assembling and meshing with 4-node tetrahedral 3-dimensional elements of type C3D4. The numbers of nodes and elements of bone and implants are shown in Table 1. An input (INP) file of the models was then entered into FE software ABAQUS 6.13 (Dassault Systems, Simulia Corp., RI). The biomechanical properties of the clavicle were assumed to be homogeneous and isotropic. The material properties of clavicle

Table 1

Numbers of nodes and elements of clavicle and implants.

Model	Clavicle		Spiral locking plate	Locking screws	Herbert screw
	Cortical bone	Spongy bone			
Node	31217	13454	32614	1217	1960
Element	131000	52929	139795	4591	6880

Table 2

Material properties used in finite element models.

Materials	Young's modulus, MPa	Poisson ratio
Cortical bone	17000	0.3
Spongy bone	1000	0.3
Titanium alloy	186400	0.3

MPa = Megapascal.

and implants in the FE models are listed in Table 2. All screws were simplified by excluding threads. The heads were retained to further study previously reported high stresses in screws.^[8]

2.3. Load and boundary conditions

Based on the complexity and multidirectional biomechanical behavior of the clavicle, 3 loading modes were simulated in this study: an 100N (Newton, N) inferior direction for cantilever bending load, an 100N axial compressive load, and an 1 Nm (Newton-meter, Nm) axial torsion (Fig. 1). An arbitrary static total force/torsion of 100N/1 Nm was equally distributed on the relevant surface nodes situated at the 15-mm most distal part of the clavicle in all loading cases.^[8] The sternal end of the clavicle was fixed in translation and rotation to avoid rigid body modes.^[23]

The contact interface of the clavicle and Herbert screw in the Herbert screw fixation model was assigned. For the spiral plate fixation model, the boundary conditions of the clavicle/screw and screw head/plate interfaces were modeled as tied interfaces. The contact interface between screw and clavicle was treated as an embedded element because the screw could not be pulled out or loosened, and contact between the plate and clavicle was defined as frictionless to avoid plate penetration into the clavicle. A coefficient of friction of 0.2 between the fractured segments was set for possible contact after loading.^[11] The mechanical properties of cortical bone, spongy bone, and titanium alloy were adopted from a previously published report.^[11]



Figure 1. Diagram showing boundary and loading conditions. The sternal side was fixed in all degrees of freedom (red). The 3 loading forces were distributed over the acromial end (purple).

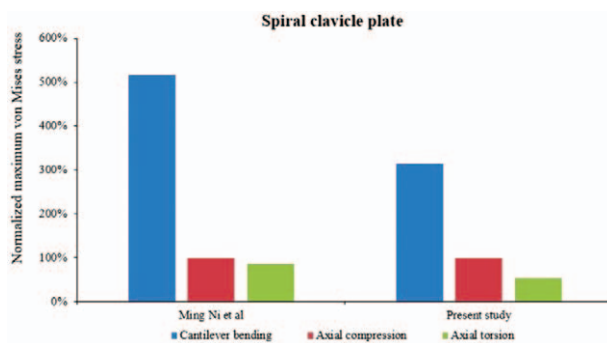


Figure 2. Normalized maximum von Mises stress of the spiral clavicle plate in 3 loading cases. The values obtained for the spiral plate in axial compression were set to 100% and served as a reference.

2.4. Analysis and validation

The stress distributions in clavicles modeling plate or Herbert screw fixation were analyzed and compared with those in model intact clavicle. The maximum von Mises stresses of the clavicle/implants were normalized to peak stresses of the intact clavicle under corresponding loading conditions.

Structural stiffness was defined as the ratio of the applied force to the average displacement of the 15-mm most distal end of the clavicle in the force direction.^[8,11] The clavicle was the major supporting structure for the shoulder movements, and mostly experienced bending and compressive loading.^[24] Comparing average displacements in bending and compressive cases allowed prediction of which implant type provided greater stability.^[25] All FE analyses were implemented in ABAQUS 6.13 software.

To validate our model, the trend of peak von Mises stresses in the spiral plate fixation model in 3 loading modes were compared with relevant experimental data from the same models.^[8]

3. Results

3.1. Model validation

Normalized maximum von Mises stresses for the spiral plate fixation model yielded trends similar to those previously reported^[11] (Fig. 2). However, disparities in results for different loadings were observed, attributable to variation in clavicle anatomy and different plate sizes.

3.2. Stress on clavicle and implants

The von Mises stress distributions for the FE models are shown in Figure 3A and B. For the intact clavicle model, the stresses were concentrated in the middle of the clavicle, in agreement with previous studies and attributable to the S-shape of the clavicle and minimal flexural rigidity of the midshaft.^[21] Peak stresses for intact clavicle were 9.57 Mpa (Megapascal, Mpa) in axial compression, 63.18 Mpa in cantilever bending and 13.08 MPa in axial torsion (Fig. 3A). In all loading modes, the spiral plate and Herbert screw fixations led to higher bone stresses than intact clavicle model. The Herbert screw fixation model showed higher bone stresses (30.14 MPa in axial compression, 304.3 Mpa in cantilever bending, 41.46 MPa in axial torsion) than those of the spiral plate fixation model (11.97 MPa in axial compression, 99.54 Mpa in cantilever bending, 25.65 MPa in axial torsion)

(Fig. 3A). The stresses in the implant models were consistently concentrated at the fracture site. The peak von Mises for the bone in fixation models were normalized to the peak stresses for the intact clavicle (Fig. 4), and showed that both Herbert screw and spiral plate fixation could lead to increased bone stress benefiting the promotion of bone healing.

For axial compression, maximum stress of the spiral plate (140.2 MPa) was higher than that of the Herbert screw (121.9 MPa) (Fig. 3B). However, for cantilever bending and axial torsion, the maximum stresses of the spiral plate (722.8 MPa and 120.1 MPa, respectively) were lower than those of the Herbert screw (1014 MPa and 174 MPa, respectively), which showed greater significant stress concentration at the fracture site (Fig. 3B). These results suggest that Herbert screw fixation is more likely than spiral plate fixation to fail in cantilever bending and axial torsion modes.

In terms of distribution of von Mises stress on bone, the Herbert screw fixation model was similar to the intact clavicle in three loading modes, with stress concentrated at the fracture site (Fig. 3A). By contrast, stress distribution in the spiral plate model was distinct from intact clavicle, being concentrated around the proximal screw holes (proximal part of the clavicle) and transmitted to the sternal end of the clavicle through the plate (Fig. 3A). These results reveal an obvious stress shielding effect from spiral plate fixation in 3 loading modes.

3.3. Micro-motions

The average displacements of the 15-mm acromial end of the clavicle in force directions were evaluated in bending and compression loading modes. Results are shown in Table 3. The average displacements showed greater similarity of the Herbert screw model to the intact clavicle model. However, the plate fixation model indicated greater stability for fracture treatment.

3.4. Structural stiffness

We normalized the magnitude of structural stiffness of the fixation models to that of the intact clavicle model (Fig. 5). We found that the spiral plate model yielded greater stiffness under cantilever bending loading modes (+714.55%), but less stiffness under axial compressive mode (-46.73%). By contrast, the Herbert screw model yielded values of -3.51% and -19.27% under axial compressive and cantilever bending modes, respectively. These outcomes revealed that the structural stiffness of the Herbert screw was lower than that of the spiral plate, and very close to that of the intact clavicle.

4. Discussion

With the development of open reduction internal fixation techniques, surgical treatment of midshaft clavicular fractures has become a focus area of contemporary orthopedic research. At present, intramedullary fixation and plate fixation are the preferred methods for treatment of midshaft clavicular fractures, based on enhanced fracture healing efficacy, reduced operating time, and lower medical costs.^[26] With increasing use of internal fixation, more research is being focused on the intrinsic properties of the clavicle and implants. However, physiological and biomechanical properties of the clavicle are not yet clearly defined, mainly because of difficulties in directly measuring those properties attributable to complex ligament and muscle attach-

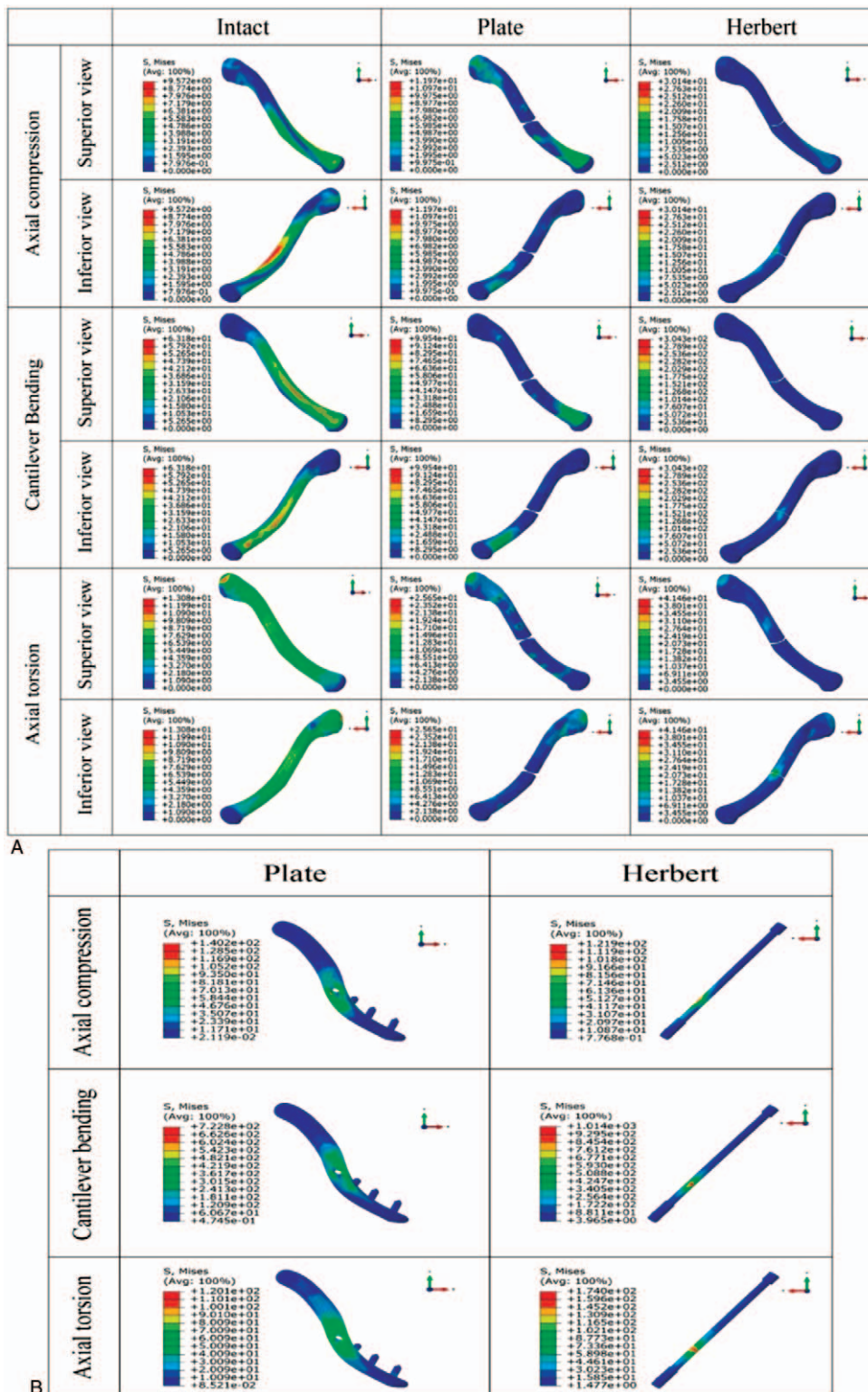


Figure 3. (A) von Mises stress distribution in the bone of the 3 FE models under 3 loading conditions. (B) von Mises stress distribution of the spiral plate and Herbert screw in 3 loading modes.

ments and the S-shape of the clavicle itself. For these reasons, FE analysis is a promising approach to evaluate the physiological and biomechanical properties of human skeleton or implants.^[27] Here, the performance of the Herbert screw and a spiral plate was

quantified using FE analysis to achieve a better understanding of the intrinsic properties of implants. Previous studies showed that the fixation strength of the spiral plate was greater than that of anterior plating, and similar to that of superior plating.^[9] Spiral

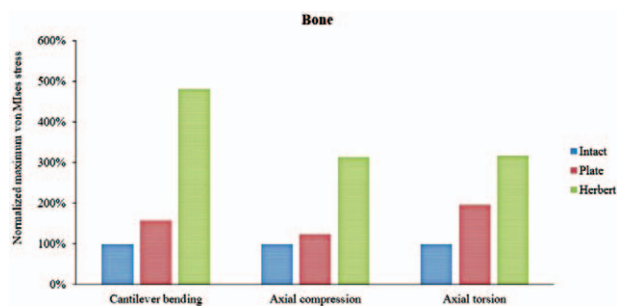


Figure 4. Peak von Mises stresses of the bone normalized to the stresses of the intact clavicle in the corresponding loading modes.

plate fixation, however, led to less skin irritation compared with superior plating.^[9] It furthermore increased multidirectional biomechanical behavior and yielded other advantages including increased bending stiffness, rotational rigidity, avoidance of neurovascular damage, and decreased hardware prominence.^[10,24,28,29] As a result, open reduction and internal fixation with the spiral clavicle plate are increasingly popular for treating displaced midshaft clavicular fractures. Although the mechanical properties of the spiral plate have been previously examined,^[8,13] relatively few studies have addressed the mechanical properties of the Herbert screw. In the present study, a midshaft clavicle fracture was modeled to simulate spiral plate and Herbert screw fixation using FE analysis and the results were validated by comparison with previously published findings. We observed differences between spiral plate and Herbert screw fixation in stress distribution and construct stiffness in axial compressive, cantilever bending, and axial torsion loading modes.

Comparing peak stresses, stress distributions and micro-motions of Herbert screw and spiral plate fixation models under 3 loading conditions, it was apparent that a certain stress was generated in the fracture ends of each fixation model. These stresses were smaller than those of the implants. There were no significant differences observed between the 2 internal fixation models. In both cases, the peak stresses were mostly concentrated on the implants. Maintaining overall stability promotes optimal bone healing, and we found that stress at the implant and clavicle contact site exhibited a smooth transition. Stress was uniformly distributed on the Herbert screw and the spiral plate. For cantilever bending loading mode, both screw and bone in the Herbert screw fixation model showed maximum stresses greater than those observed for the spiral plate fixation model. The results for axial torsion loading mode were similar to those obtained for cantilever bending loading mode. This may be because of the longer arm of force of the Herbert screw generating longer torque than the spiral plate. For the axial compression loading mode, maximum stress of the fixation (121.9 Mpa) in the Herbert screw model was lower than that

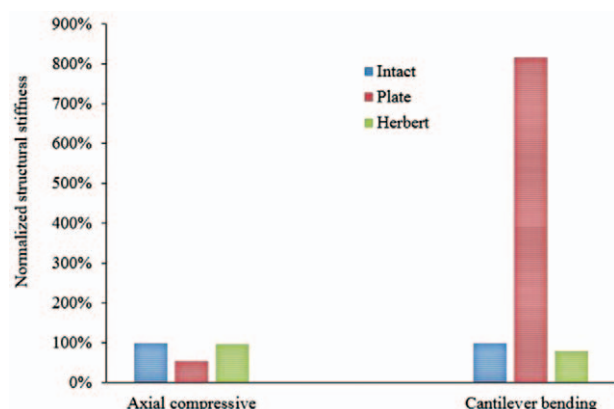


Figure 5. Comparison of structure stiffness normalized by the magnitude represented in the intact clavicle model under axial compressive and cantilever bending loading modes.

(140.2 Mpa) in the spiral plate fixation model. However, the maximum stress of the clavicle (30.14 Mpa) in the Herbert screw fixation model was greater than that (11.97 Mpa) in the spiral plate fixation model. Conceivably, the Herbert screw design generates more compression. It is known that appropriate compression stress at the fracture ends can accelerate bone healing.^[14] Obviously, in the cantilever bending loading mode, the Herbert screw fixation had greater peak implant and bone stress compared to spiral plate fixation. The maximum stress on the Herbert screw was beyond the yield stress of the Ti6Al4V titanium alloy based on ISO 5382-3. Use of the Herbert screw may therefore result in implant failure. It was shown that the maximum force acting on the clavicle that approximated arm abduction was 100 N.^[30] Based on this, we believe that Herbert screw fixation is appropriate for treating simple displaced midshaft clavicular fractures, but the affected limb should be spared during the early postoperative period to prevent excessive implant and bone stress leading to implant failure and interference with bone union.^[14,25]

The comparative analysis of structural stiffness showed that the structural stiffness of the Herbert screw model is close to but slightly lower than that of the intact clavicle model in both cantilever bending and axial compression modes. The different shapes of the implants may explain the different outcomes. In the present study, we showed that in the cantilever bending loading mode, the structural stiffness of Herbert screw was lower than that of spiral plate. Therefore, spiral plate fixation model yields greater stability and may be preferable for patients who require early postoperative weight bearing.

Our results suggest that for simple displaced midshaft clavicular fractures, Herbert screw fixation provides less structural stability and higher probability of failure than spiral plate fixation, based upon greater displacement of 15-mm acromial end and greater peak bone and implant stress across three loading modes. On the basis of the stress distributions for the fixation models, we conclude that both Herbert screw and spiral plate fixation are suitable and stable for the treatment of midshaft clavicular fracture. Because spiral plate fixation imparts more rigid stabilization, maintains the length of bone, and facilitates early mobilization, it is more suitable for treating comminuted midshaft clavicular fractures and for meeting the needs of patients demanding an early return to activities.^[31]

Table 3
Average displacements of uniform position of each model under axial compressive and cantilever bending loading modes (millimeter).

Model	Intact	Plate	Herbert
Axial compressive	0.059	0.111	0.057
Cantilever bending	3.064	0.335	3.795

Spiral plate and Herbert screw fixation each have advantages and disadvantages. Plate fixation may provide more rigid stabilization than Herbert screw fixation, facilitating early mobilization and stable, multidirectional support for midshaft clavicular fractures.^[32] However, spiral plate fixation requires relatively larger incisions and extensive exposure, increasing the risk of scarring, infection, and refracture after removal of the plate.^[25,33] Intramedullary devices, by comparison, are more sparing of the skin, vascular, and nerve structures, require smaller incisions and reduce the likelihood of infection and subsequent complications.^[34] They permit axial compression and provide relatively stable fixation beneficial for healing.^[32] However, intramedullary devices such as Kirchner wires which have smooth surfaces, pointed ends, and varying degrees of pin length protrusion from the clavicle are prone to migration and may provide low initial torsional support.^[35] The Herbert screw is usually considered permanent^[2] which reduces the possibility of additional operations and promotes cost-saving and greater patient satisfaction.

Fracture micromotion is linked to fixation type and plays a key role in the bone healing process.^[36] Previous studies indicate that micromotions of 0.15 to 0.4 mm can promote bone healing if the fracture gap is no >3 mm.^[37] In our study, the relative fracture micromotions were less than 0.4 mm under cantilever bending and axial compression loading modes at 15 mm from the distal end of the clavicle for both internal fixation models, approximating main shoulder activities. These results suggest that both Herbert screw and spiral plate fixation are applicable and effective.

Some limitations of the present study should be noted. First, a young female Chinese subject was used for simulations, and the Chinese female clavicle is reportedly shorter and narrower than that of a Chinese male. Clavicle geometric variation was not addressed in our study.^[38] Second, we used a relatively simple model of midshaft clavicle fracture and clavicle and implant models were analyzed in the absence of muscles and ligaments. In actuality the clavicle is exposed to various forces and moment angles in day-to-day shoulder movement.^[11] Third, the FE models were not validated by biomechanical test results. These limitations notwithstanding our findings provide a comparison of mechanical behaviors of Herbert screw and spiral plate fixation for midshaft clavicular fractures under identical conditions and assumptions. The findings will need to be corroborated by the results of randomized controlled trials including long-term follow-up.

To sum up, we compared the stabilizing mechanisms of Herbert screw and spiral plate fixation. Herbert screw fixation showed stress distribution similar to intact clavicle under all loading conditions, but provided less stability than did spiral plate fixation. We conclude that Herbert screw fixation is suitable for the treatment of simple displaced clavicular fractures. Postoperatively, excessive shoulder activities and weight-bearing should be avoided. Spiral plate fixation provides greater stability, but is associated with stress shielding. Spiral plate fixation may therefore be preferred for patients requiring an early return to activity.

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