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Finite Element Analysis of External Fixation for Mid-Shaft Clavicle Fractures Using Locking Compression Plates

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Abstract

Clavicle implant models were accurately engineered in this study to simulate the stiffness features of an external locking compression plates (LCP) fixator used in managing mid-shaft clavicle fractures. The research systematically assessed 4-screw, 6-screw, and 8-screw configurations under varying load conditions, including axial compression, torsion, and 4-point bending. The results underscore the biomechanical superiority of the 6-screw configuration, which demonstrated enhanced stiffness values of 124.39 N/mm in axial compression, 322.71 N.mm/degree in torsion, and 1,023.02 N/mm in 4-point bending. These findings surpass those associated with unilateral methods, where stiffness values range from 117 to 126 N/mm under axial compression. The study offers critical insights into the optimization of fracture management, positing that the 6-screw configuration provides considerable biomechanical advantages. Surgeons can use these findings to make informed decisions about screw configurations, potentially improving clinical outcomes by reducing hospitalization periods, re-operation rates, and complication risks. This research contributes to more effective resource management in the surgical treatment of mid-shaft clavicle fractures.

Keywords: Clavicle; External fixation; Finite element analysis; Locking compression plate; Stiffness.
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1. Introduction

Mid-shaft clavicle fractures are prevalent injuries, especially among young, active individuals, often resulting from direct trauma to the shoulder girdle.[1] The treatment of these fractures can be either nonoperative or operative, depending on variables such as the extent of displacement, degree of shortening, and the patient's activity level. Nonoperative management typically involves immobilizing the arm with a sling or a figure-of-eight bandage, thereby facilitating natural fracture healing.[2] However, in cases of significant displacement or shortening, surgical intervention may be warranted to ensure proper alignment and optimal healing.

Open reduction and internal fixation (ORIF) with plates and screws is a principal surgical approach for the treatment of mid-shaft clavicle fractures.[3] Orthopedic surgeons can enhance the application of locking plate fixation in clinical practice by integrating the findings of this research.[4,5] This technique involves a precise incision over the fracture site, realignment of the bone fragments, and stabilization with a metal plate and screws. ORIF offers stable fixation, promoting early mobilization and reducing the risk of nonunion. However, it is also associated with potential complications, including infection, hardware irritation, and the possibility of requiring a second surgery for hardware removal. The continuous study of various design characteristics is crucial, as it provides valuable insights that can guide orthopedic surgeons in selecting the most appropriate fixator device tailored to the specific needs of each patient.[6] This evidentiary support significantly contributes to the ongoing discourse within the orthopedic community regarding optimal management paradigms for mid-shaft clavicle fractures.[7–10] Numerous researchers have explored the combination of surgical fixation with suture anchor fixation, recognizing it as a promising strategy to expedite patient rehabilitation.[11–18] Additionally, dual plating has been demonstrated as an effective method for treating bipolar clavicle fractures.[19]

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Intramedullary (IM) fixation represents an alternative surgical approach, involving the insertion of a metal rod or nail into the marrow canal of the clavicle.[20] This technique is less invasive than open reduction and internal fixation (ORIF), typically resulting in smaller scars and reduced soft tissue damage. IM fixation is particularly advantageous for patients requiring an expedited return to physical activity, as it facilitates early shoulder mobilization. However, this method may not provide the same level of rigid fixation as ORIF, and there is a potential risk of rod migration or irritation.

In addition to traditional methods, external fixation techniques have also been investigated for the management of mid-shaft clavicle fractures.[2] These techniques utilize small incisions and specialized instruments to achieve external alignment and stabilization of the fracture. Percutaneous fixation has the potential to minimize surgical trauma and expedite recovery; however, research on this approach remains limited.

The exploration of external fixation techniques for mid-shaft clavicle fractures has emerged as a central theme in contemporary orthopedic research, with scholars diligently investigating novel approaches to enhance therapeutic outcomes. One such technique receiving considerable attention is the use of locking compression plates (LCP), which have been rigorously analyzed through finite element analysis (FEA). The scholarly literature has produced promising results, highlighting the efficacy of the LCP technique. A pioneering study used FEA to assess the biomechanical stability of LCPs versus traditional non-locking plates in femoral fractures.[21,22] The findings demonstrated superior stability and reduced displacement with LCP, reinforcing its potential as an effective external fixation method.[23] Notably, the optimal mechanical properties were observed in fixators with unilateral mechanical characteristics.[24]

A sophisticated computational modeling technique, FEA serves as a pivotal tool for simulating the mechanical behavior of biological structures, thereby offering researchers critical insights into the efficacy of various fixation methodologies. In the context of mid-shaft clavicle fractures, the application of locking compression plates aims to stabilize the fracture site and promote accelerated healing. Through the simulation of mechanical forces and stresses exerted on the clavicle during activities such as lifting or arm movements, FEA allows for a precise examination of the performance characteristics of different fixation techniques under varying conditions. This methodological approach provides clinicians and orthopedic surgeons with essential data, enabling informed decisions regarding the most suitable external fixation method for their patients. Researchers have effectively utilized FEA to comprehensively analyze the biomechanical aspects of using locking compression plates for mid-shaft femoral fractures.[21] Moreover, FEA has validated that combining coracoclavicular fixation with acromioclavicular joint repair offers superior stability in both vertical and horizontal planes, while also reducing stress on the suture button, making it an effective treatment for high-grade injuries.[25]

The application of computational modeling techniques not only enhances our understanding of biomechanical dynamics but also facilitates the advancement of more effective and patient-specific treatment strategies. In this study, clavicle implant models were precisely developed to simulate the stiffness characteristics in compression, torsion, and bending of an external LCP fixator employed in the management of mid-shaft clavicle fractures. The stiffness of various clavicle configurations, including 4-screw, 6-screw, and 8-screw fixations, was evaluated under axial compression, axial torsion, and 4-point bending load directions.

2. Materials and methods

The clavicle implant models were designed based on the bone characteristics detailed by Sumanont *et al*.,[25] were intricately designed using PowerShape software, a product of Autodesk Inc. based in San Rafael, California, USA. After model generation, the simulation process was meticulously conducted using ANSYS Workbench software, an advanced computational tool developed by ANSYS Inc. headquartered in Canonsburg, Pennsylvania, USA. This methodological approach aligns with current practices in the field, ensuring precision and reliability in the analytical procedures employed for the study as shown in Fig. 1.

2.1 Material property

In a finite element model, boundary conditions impose constraints by securing certain degrees of freedom at specific points. Concurrently, loadings define the external forces or pressures applied. For accurate clavicle simulations under external fixation, precise boundary conditions, and loadings are essential. Creating a finite element model for such applications requires a deep understanding of the issue, anatomical details, and experimental validation. The choice of material properties for the implant model significantly influences its interaction with surrounding tissues, affecting its strength, durability, and biocompatibility. Proper material selection ensures reliable simulation results, as shown in Table 1.

Table 1: The material properties used for the implant model.[22]

Material	Young's Modulus (MPa)	Poisson's Ratio
Bone	805	0.30
Stainless steel 304	193,000	0.31

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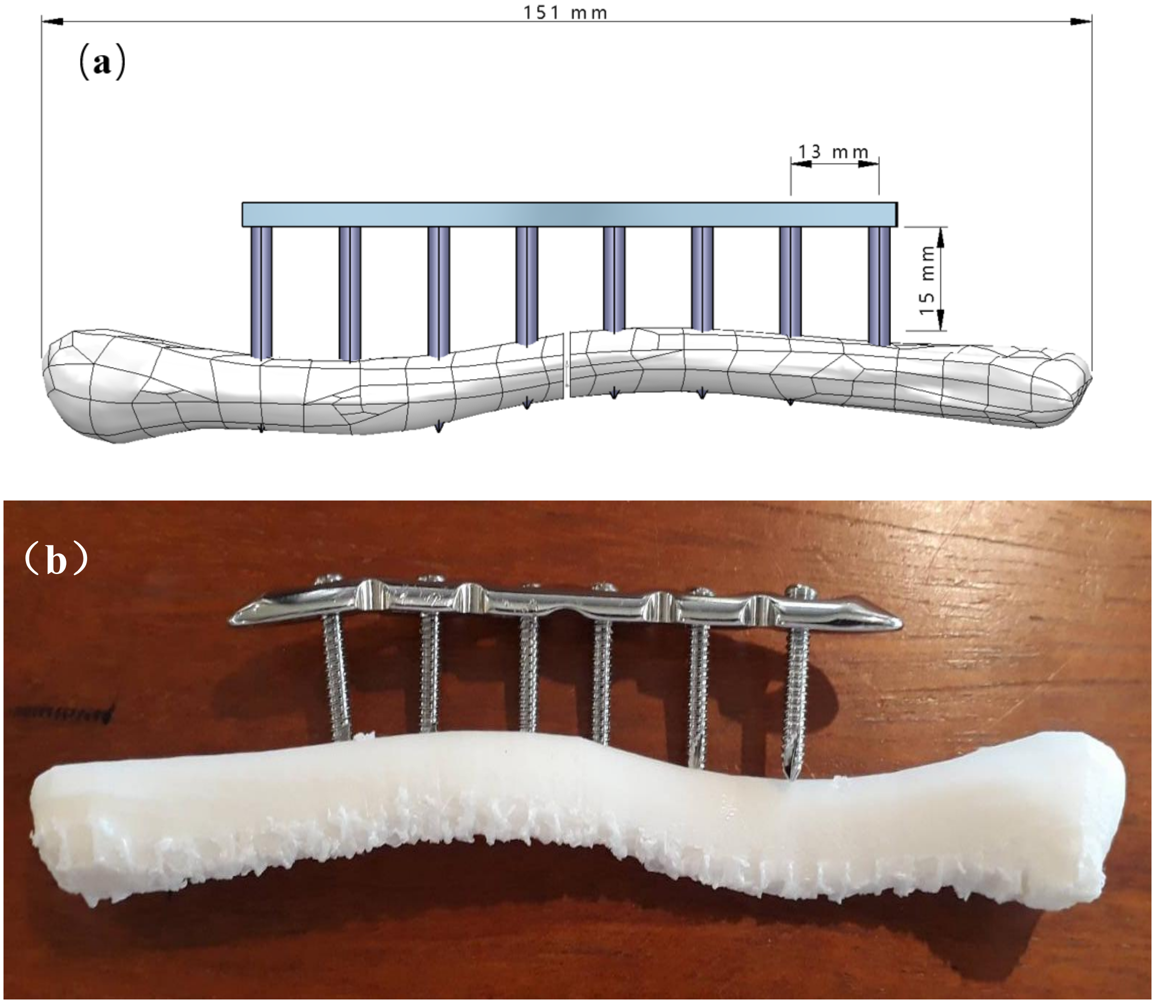

Fig. 1: The external fixation of the clavicle using an implant model equipped with LCP (a) the simulation model representation and (b) the actual device image.

2.2 Finite element methods

The finite element method (FEM) is a widely utilized numerical technique for addressing complex engineering challenges, particularly in structural analysis. In the context of modelling tibial external fixation, a pertinent mathematical model is developed using FEA. This model is governed by factors such as material properties, geometry, and loading conditions, which collectively inform the requisite equations. For tibial external fixation, a general structural equation based on force equilibrium is employed, typically framed within the context of linear elastic analysis. This equation can be simplified and represented through finite elements, as illustrated in Eq. (1).

$$\mathrm{K.U} = \mathrm{F} \tag{1}$$

In this context, the stiffness matrix is represented by K (N/mm), the displacement vector by U (m), and the force vector by F (N). By integrating the cross-sectional moment of inertia (I) (m^4) and Young's modulus (E) (MPa), one can determine the cross-sectional bending stiffness (EI). Eq. (2) provides an expression for this relationship. Crucially, four-point bending tests are used to experimentally evaluate lateral bending stiffness, from which EI is obtained.

$$\mathrm{k} = \frac{48\mathrm{EI}}{\mathrm{L}^3} \tag{2}$$

where the stiffness is k (N/mm), and the distance between supports is indicated by L (m). Material characteristics like Poisson's Ratio (υ) and Young's Modulus are taken into consideration by the stiffness matrix. Eq. (3) expresses the constitutive matrix (D) for isotropic linear elastic materials.

$$\mathrm{D} = \frac{\mathrm{E}}{(1+\nu)(1-2\upsilon)} = \begin{bmatrix} 1-\upsilon & \upsilon & \upsilon & 0 & 0 & 0 \\ \upsilon & 1-\upsilon & \upsilon & 0 & 0 & 0 \\ \upsilon & \upsilon & 1-\upsilon & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\upsilon}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\upsilon}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\upsilon}{2} \end{bmatrix} \tag{3}$$

The relationship between the stress and the strain in linearly elastic materials, described by Hooke's Law, is

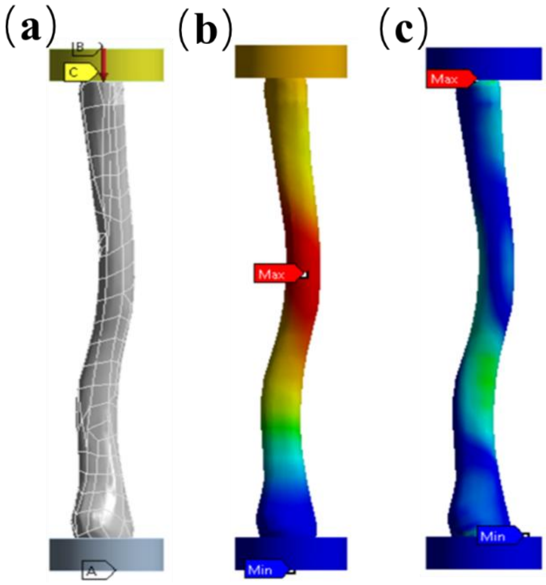

Fig. 2: The normal clavicle bone testing (a) boundary condition, (b) deformation and (c) stress.

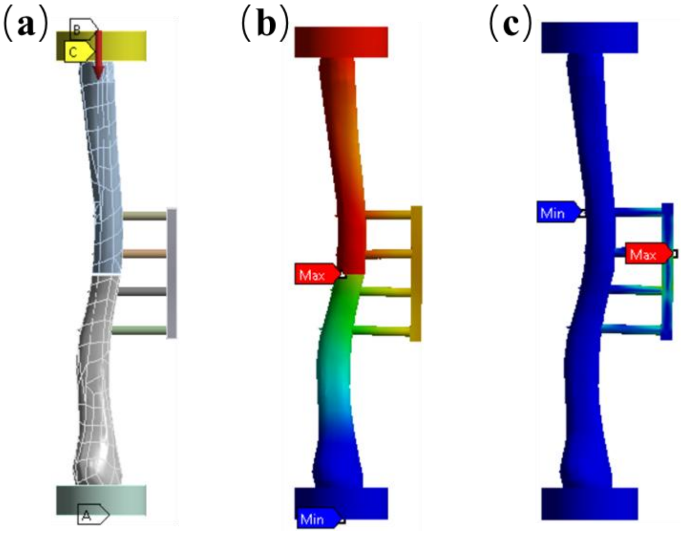

Fig. 3: The 4-screw fixation compression testing (a) boundary condition, (b) deformation and (c) stress.

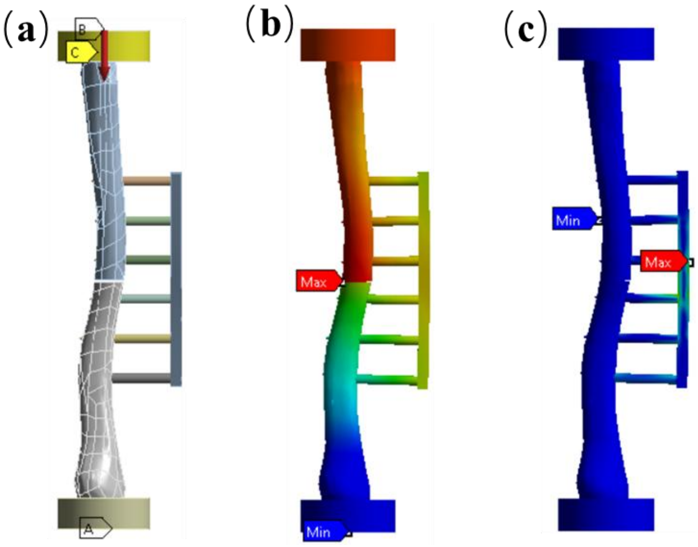

Fig. 4: The 6-screw fixation compression testing (a) boundary condition, (b) deformation and (c) stress.

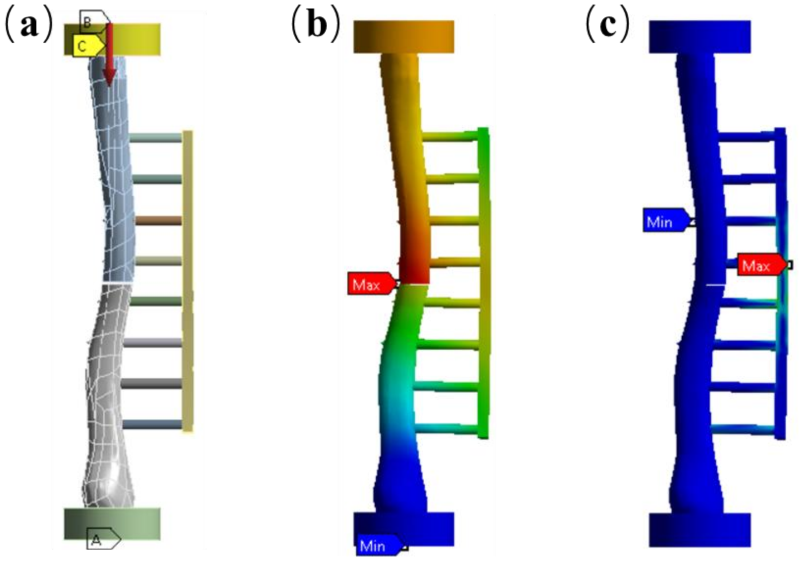

Fig. 5: The 8-screw fixation compression testing (a) boundary condition, (b) deformation and (c) stress.

depicted in Eq. (4).[26

$$\sigma = \mathrm{E}.\varepsilon \tag{4}$$

where σ (MPa) denotes the applied stress, and ε represents the corresponding strain.

3. Results and discussion

This investigation assesses the mechanical behavior of LCP in different clavicle configurations, including 4-screw, 6-screw, and 8-screw fixations, utilizing FEA. By simulating the application of the LCP in patients who have undergone surgery for clavicle fractures, the study conducts a detailed analysis of the LCP's performance under axial compression, axial torsion, and 4-point bending conditions. The specific results are provided below. In the simulation model of external clavicle fixation, the researchers assumed the clavicle to be a homogeneous structure and analyzed it under isotropic conditions.

3.1 Compression testing

The specified boundary condition entails applying an axial compression load of 200 N while rigidly fixing the distal clavicle bone in place, as illustrated in Figs. 2(a), 3(a), 4(a) and 5(a). Figs. 2-5 illustrate the findings from the reassessment of axial compression testing, which are comprehensively outlined in Table 2.

A notable advantage of employing FEA simulation lies in its capacity to accurately identify the location of maximum displacement, which is indicative of the fracture site. Upon the application of pressure to the distal end of the clavicle, fractures predominantly occur within the middle shaft, as demonstrated in Fig. 2(b), where the maximum deformation was recorded at 1.0287 mm. This information is essential for the medical team, facilitating precise diagnostic assessments of the injury. It was observed by our research team that the patient sustained a clavicle fracture in the middle section of the bone, primarily caused by a lateral impact. In the implant model, the highest deformation at the fracture site is depicted in Figs. 3(b), 4(b), and 5(b), with corresponding deformations of 1.7789 mm, 1.6068 mm, and 1.5331 mm, respectively. A reduction in deformation was observed as the number of screws in an external fixation utilizing an LCP increased during compression testing, attributable to the improved biomechanical stability and load distribution.[27]

In all LCP models, the maximum stress is observed at the head screw located near the fracture site in the direction of the applied load, as depicted in Figs. 3(c), 4(c), and 5(c), with stress values of 842.50 MPa, 836.11 MPa, and 785.66 MPa, respectively. This is the critical point where initial failure is likely to occur under axial compression. The addition of more screws enhances the distribution of mechanical loads across the fixation construct. Each additional screw contributes to load sharing, thereby reducing the stress on individual screws and the plate. This load-sharing mechanism prevents excessive strain on any single component, decreasing the likelihood of deformation and failure. For example, an 8-screw configuration distributes compressive forces more evenly than a 4-screw configuration, resulting in reduced deformation and increased stability.

The 8-screw LCP construct exhibited the highest stiffness and yield load, followed by the 6-screw and 4-screw configurations. Notably, the 4-screw construct achieved the most uniform load distribution across each screw within the LCP, while the 8-screw configuration offered superior resistance to axial compression forces, as evidenced by the lowest observed deformations.[27] This increased stiffness and reduced deformation are advantageous for maintaining fracture alignment under physiological loads, minimizing micromotion at the fracture site, and potentially expediting the healing process.[28] However, these benefits are accompanied by a trade-off, including heightened surgical complexity and an increased risk of soft tissue disruption.[29]

Table 2: The results of forces operating in axial compression testing

Compression test			
Model	Max. Deformation (mm)	Max. Stress (MPa)	Stiffness (N/mm)
Normal Bone	1.0287	21.99	194.42
4 Screw	1.7789	842.50	112.43
6 Screw	1.6078	836.11	124.39
8 Screw	1.5331	785.66	130.45

3.2 Torsion testing

Torsion testing serves as a critical method for assessing the resistance of a fixation construct to twisting forces, a key determinant of its mechanical stability. A significant parameter in evaluating the performance of LCP is its response to torsional loads, which induce rotational forces between the bone and the plate. This testing is instrumental in determining the LCP's efficiency in withstanding such forces, ensuring the maintenance of proper alignment and structural integrity of the fixation. For this analysis, a torsional load of 3,000 N.mm is applied, with the distal clavicle bone securely immobilized, as illustrated in Figs. 6(a), 7(a), and 8(a). The results from the torsion testing reassessment are visually represented in Figs. 6-8 and thoroughly presented in Table 3.

Empirical studies have demonstrated that increasing the number of screws in an external fixation configuration with LCP markedly reduces deformation under torsional loading. This reduction in deformation is primarily due to the enhanced mechanical interlock established between the plate and the bone. Each screw within the LCP construct contributes to the overall fixation by securely anchoring the plate to the bone, thereby counteracting torsional forces. As the number of screws increases, the fixation construct becomes more rigid, thereby improving the plate's resistance to twisting. This increased rigidity ensures that the LCP maintains proper alignment of the fracture fragments, thereby minimizing the risk of rotational displacement, a complication particularly detrimental in long bone fractures.

Research has demonstrated that increasing the number of screws in external fixation with LCP significantly reduces the stress exerted on both the plate and the bone during torsional loading. The principal mechanism behind this stress reduction with an increased screw count is the improved distribution of torsional loads. Each screw in the LCP construct acts as a fixation point, securing the plate to the bone and facilitating the even distribution of applied forces. As the number of screws increases, the torsional load is dispersed across a greater number of fixation points, thereby reducing stress concentration on individual screws, as well as on the plate and bone. FEA studies have confirmed that the addition of screws results in a more uniform stress distribution, which not only decreases the maximum stress experienced by the construct but also mitigates the risk of mechanical failure. Furthermore, the maximum stress concentration is identified at the head screw near the top fixture in the 4-screw and 6-screw configurations, whereas in the 8-screw configuration, the peak stress occurs at the bottom fixture. This is demonstrated in Figs. 6(c), 7(c), and 8(c), with corresponding stress values of 803.47 MPa, 758.64 MPa, and 745.17 MPa, respectively. These findings indicate the critical points where structural failure is likely to initiate. Unlike conventional screws, which stabilize through friction with the bone, locking screws secure themselves by locking into the plate, creating a more rigid and stable construct.[30,31]

Additional screws augment the structural stiffness of LCP by fortifying its attachment to the bone. A principal factor driving this increase in stiffness is the enhanced distribution of loads throughout the LCP construct. Each screw within the LCP system serves to anchor the plate to the bone, thereby distributing the applied torsional forces over a more extensive area. As the number of screws increases, the load is dispersed across multiple fixation points, which mitigates localized deformation and augments the overall rigidity of the construct. Moreover, the enhancement in stiffness with the addition of screws is attributable to the reduction in relative movement between the plate and the bone. An increased number of screws secures the plate more firmly, thereby minimizing the relative motion at the screw-bone interfaces. This reduction in movement significantly improves the construct's ability to withstand torsional forces, thereby further increasing its stiffness.

Table 3: The results of forces operating in the torsion direction

Torsion test			
Model	Max. Deformation (degree)	Max. Stress (MPa)	Stiffness (N.mm/degree)
4 Screw	13.0650	803.47	229.62
6 Screw	9.2961	758.64	322.72
8 Screw	5.8668	745.17	511.35

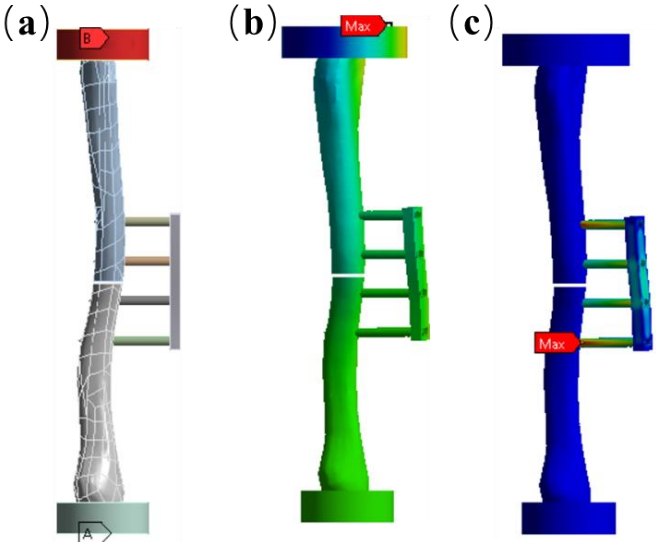

Fig. 6: The 4-screw fixation torsion testing (a) boundary condition, (b) deformation and (c) stress.

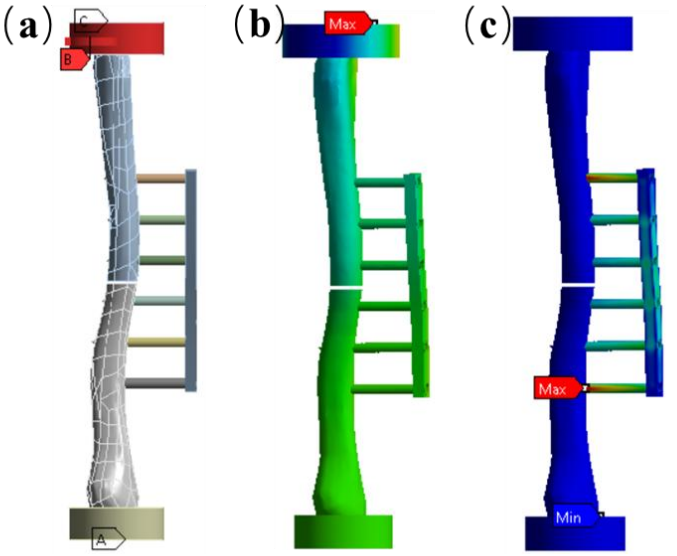

Fig. 7: The 6-screw fixation torsion testing (a) boundary condition, (b) deformation and (c) stress.

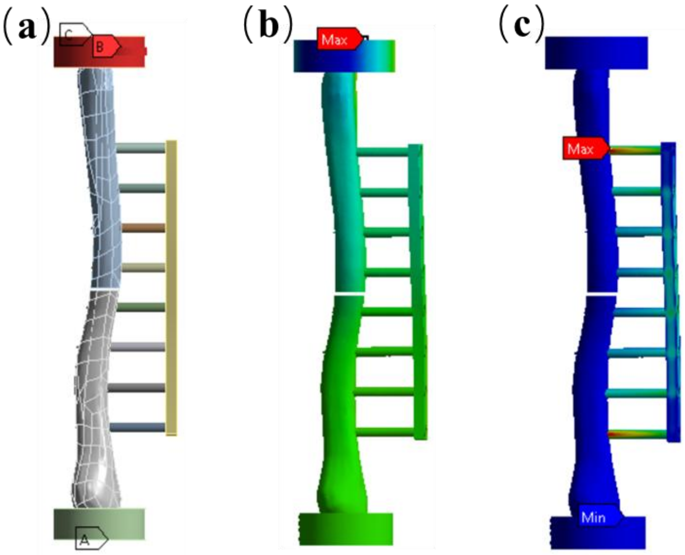

Fig. 8: The 8-screw fixation torsion testing (a) boundary condition, (b) deformation and (c) stress.

3.3 Bending testing

Figs. 9(a), 10(a), and 11(a) illustrate the experimental setups for the 4-point bending tests, along with a comprehensive assessment of the mechanical performance of the 4-screw, 6-screw, and 8-screw external fixation systems under varying loading conditions. In these setups, a vertical load of 200 N is applied to the upper surface while the lower surface remains fixed.

Figs. 9-11 provide a visual representation of the reassessment of 4-point bending for external fixation using LCP on clavicle fractures, which are methodically summarized in Table 4.

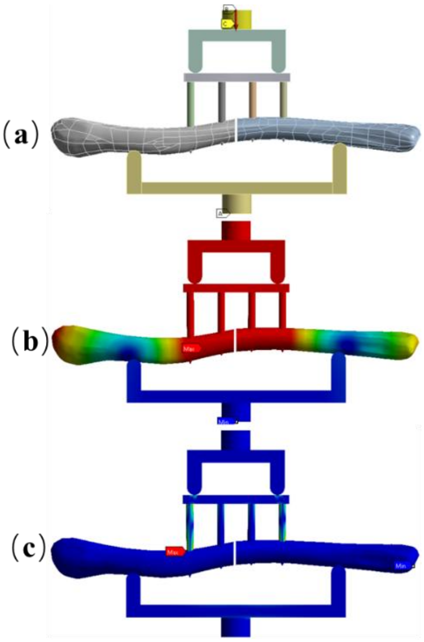

Fig. 9: The 4-screw fixation 4-point bending testing (a) boundary condition, (b) deformation and (c) stress.

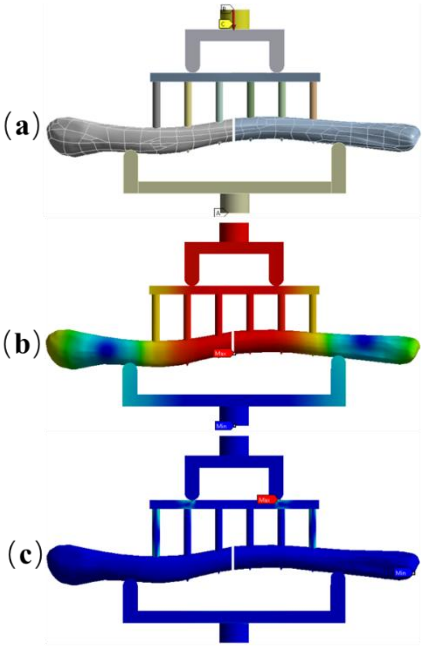

Fig. 10: The 6-screw fixation 4-point bending testing (a) boundary condition, (b) deformation and (c) stress.

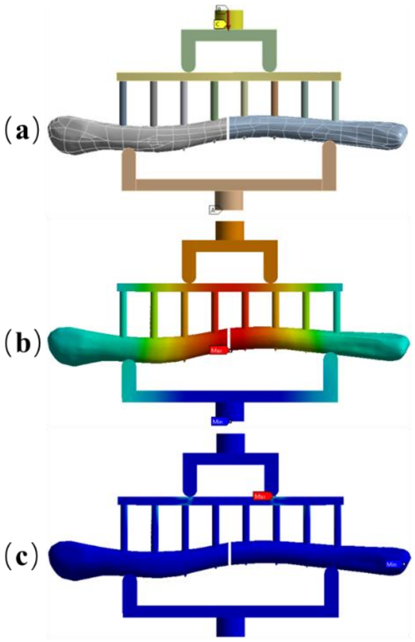

Fig. 11: The 8-screw fixation 4-point bending testing (a) boundary condition, (b) deformation and (c) stress.

Table 4: The results of forces operating in various directions.

4 Point Bending			
Model	Max. Deformation (mm)	Max. Stress (MPa)	Stiffness (N/mm)
4 Screw	0.6500	287.79	307.69
6 Screw	0.1955	347.47	1,023.02
8 Screw	0.1669	519.76	1,198.32

Bending tests are essential for evaluating the mechanical behavior of fixation devices by simulating physiological loads representative of forces encountered during routine activities. These tests provide critical insights into how well LCP performs under bending stresses. A significant aspect of this evaluation is the deformation experienced by the LCP system when subjected to bending loads. The degree of deformation is closely linked to the number of screws incorporated in external fixation setups.

Increased screw density is typically correlated with a reduction in deformation observed during bending tests. The addition of screws enhances the stability of the LCP system by facilitating a more effective distribution of bending forces across the plate. This improved distribution mitigates localized stress concentrations, thereby diminishing the overall deformation of the fixation construct. As a result, the ability to maintain accurate fracture alignment is substantially enhanced, reducing the risk of malunion and instability. The observed reduction in deformation with higher screw density highlights the critical importance of optimizing screw placement to achieve optimal mechanical stability and support.

The evaluation of maximum stress is crucial when assessing bending forces in clavicle implants. As the number of screws increases, the maximum stress also rises, which contrasts with the results observed in compression and torsion tests. Locking plates are specifically designed to convert shear stress into compressive stress at the screw-bone interface, leveraging the bone's superior resistance to compression to enhance fixation stability. Among the various LCP configurations tested, the 8-screw implant demonstrated the highest maximum stress, outperforming both the 6-screw (near the locking plates) and 4-screw (near the bone) fixations. While the 4-screw fixation provided a more uniform load distribution along the LCP, as shown by the stress at each screw in Figs. 9(c), 10(c), and 11(c), and resulted in the lowest stress, the 8-screw design offered superior resistance to bending forces, highlighting its effectiveness in maintaining structural integrity under mechanical stress. However, due to the risk of causing excessive stress on the bone, surgeons may prefer to avoid using an LCP that induces high maximum stress. Based on the experimental results, the 4-screw configuration is not recommended for clinical application.

Stiffness quantifies a fixation system's resistance to bending deformation. Bending tests reveal that the stiffness of the LCP system typically increases with the number of screws employed. The addition of screws enhances the anchorage of the plate to the bone, thereby minimizing relative movement between the two components. This reduction in movement contributes to a more rigid fixation construct, improving its overall rigidity. These findings are substantiated by FEA, which provides simulations of LCP systems subjected to bending loads. FEA analyses consistently show that a higher number of screws leads to improved overall stiffness of the fixation system, enhancing its capability to resist bending forces and maintain structural integrity.

4. Conclusion

Clavicle implant models were meticulously designed to replicate the stiffness characteristics in compression, torsion, and bending of an external LCP fixator used in treating mid-shaft clavicle fractures. Various configurations, including 4-screw, 6-screw, and 8-screw fixations, were evaluated for stiffness under axial compression, axial torsion, and 4-point bending load applications. The study yielded several key conclusions. First, the research identified the optimal screw configuration by analyzing mechanical behavior, including stress and deformation distribution, and evaluating load-bearing capacities. These insights contribute significantly to optimizing fracture management methods. Second, the biomechanical benefits of the 6-screw configurations were highlighted, with stiffness values of 124.39 N/mm (axial compression), 322.71 N.mm/degree (axial torsion), and 1,023.02 N/mm (4-point bending load). Academic research supports critically reviewing the use of LCP for 6-screw fixation, as they surpass unilateral methods in stiffness. Specifically, Lang Yang et al. reported stiffness values ranging from 117 to 126 N/mm under axial compression. Finally, these findings allow surgeons to make informed decisions on screw configurations for LCP external fixations. These choices significantly impact treatment outcomes, leading to shorter hospitalizations, reduced re-operation rates, and fewer complications. These advantages also promote effective resource management.[32]

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Supporting Information

Not applicable.

Conflict of Interest

There are no conflicts to declare.

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