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Applications of Finite Element Methods and Discrete Particle Swarm Optimization Algorithms in Design of Locked Compression Plates

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ABSTRACT

Locked compression plates have been widely used for the treatment of diaphyseal femoral fractures. The purpose of this study was to discover the best screw configurations in the twelve-hole bone plate by using a biomechanical optimization method namely finite element analysis-based discrete particle swarm optimization. The results showed that increasing the number of screws decreased the deflection of the constructs, and the performance of three screws per main segment showed no significant difference as compared to all screws occupying the plate holes. We concluded that stability can be achieved by increasing the number of screws and three screws on either of the segment can provide sufficient stability while minimizing the complications of plate fixation.

Keywords: locked compression plate, particle swarm optimization, FEA, femur.
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1 INTRODUCTION

Locked compression plate has become a commonly used technique for treating femoral shaft fractures and nonunions [1-2],[5]. Instability of a long bone during fractures could affect its bone healing. Stability is the amount of strain at the fracture site, and the strain represents the type of healing that can occur [2]. The stability could be influenced by several factors, such as working length (the distance from the first screw to the fracture site of each fragment), fracture gap size, distance between the bone and the locked compression plate, material properties, number of locking screws, and location of locking screws. Those factors have been researched by some studies [1],[12]. However, determining the number and the location of the screws are still based on the clinical experiences as described in numerous studies [3-4],[6],[11],[13-14]. The question about how many screws are needed in the proximal and distal fragments is still under debate [2]. Some studies have recommended that at least two screws should be placed on either of fragment for the simple fractures and comminuted fractures, respectively [2],[12]. In order to investigate the fixation stability of the bone, different numbers and positions of the screws used in locked compression plates have been selected by the researchers. In fact, there are a lot of combinations of the screws which can be placed in some location of the plate holes of locked compression plates. There would be more than 1,000 possible locations for combination of four, five, six, seven, eight or nine screws in twelve-hole locked compression plate, respectively. Therefore, it is impossible for the researchers to attempt to find the best configuration by conducting a biomechanical test, besides, it will cost a lot of money. In this study, we presented a novel biomechanical optimization method namely finite element analysis-based discrete particle swarm optimization to address all those limitations. The purpose of this study was to discover the best screw configuration of the locked compression plate. Thus, it could help the surgeons to select the suitable screw's location and number on the twelve-hole plate for the patients during treatment of femoral shaft fractures.

2 MATERIALS AND METHODS

2.1 Finite Element Analyses

Finite element analysis consists of a mathematical equation of physical situation, loading conditions, and boundary conditions. Several problems may be modeled to determine their behavior under various conditions. In this study, three-dimensional finite element models, which included the locked compression plate, the locking screws, and long bone, were developed and analyzed by using ANSYS 11.0 (ANSYS, Inc., Canonsburg, PA, USA). The modeling processes included: bone modeling, fractures modeling, and implants modeling. The bone was modeled as hollow cylinder (24 mm in outer diameter, 16 mm in inner diameter, and 237 mm in length). A 5-mm fracture gap was modeled to simulate the fracture. This fracture was treated with use of twelve-hole locked compression plate (Fig. 1a). All locking screws were bicortical and the distance between the bone and the locked compression plate is 2 mm. These factors have an agreement with Ahmad et al. [1] that can allow a better blood supply. The locked compression plate and the locking screws were made of stainless steel with an elastic modulus of 230 GPa and a Poisson's ratio of 0.3. The elastic modulus of the bone was 17 GPa and the Poisson's ratio was 0.3. In addition, a Young's Modulus of 0 GPa and a Poisson's ratio of 0.01 were used to represent the unoccupied screw holes.

Twenty-node hexahedral elements (SOLID 95) have been chosen to mesh the locked compression plate, the locking screws, and the bone. In order to accelerate the optimization process, the number of the elements of the numerical model should be as small as possible. Thus, numerical convergence was performed and the solutions were considered accomplished when the variation of the result of the sequential analysis was less than 5 %. A cantilever bending was considered, which is compromised with Tornkvist et al. [13]. In the loading and boundary conditions, a point load of 150 N at the end of the bone fragment was assumed and the degrees of freedom at the end of another bone fragment were fully restrained (Fig. 1b). The interface conditions between the locked compression plate and the locking screws were assigned to be bonded. Furthermore, the bonded condition was also applied to the interface between the locking screws and the bone. In the postprocessing analysis, the maximum displacement was used to evaluate the fixation stability of the locked compression plate.

2.2 Discrete Particle Swarm Optimization

Particle swarm optimization (PSO) was originally developed by Eberhart and Kennedy in 1995. PSO is a population based optimization stochastic technique inspired by the behavior of bird flocking or fish schooling. PSO has many similarities with another evolutionary computation technique such as genetic algorithm (GA). The system is initialized with a population of individuals placed on the search space randomly and searching for the optimal solution by updating individual generations. However, PSO has no evolution operators such as crossover and mutation. The main strength of PSO is its fast convergence and easy to implement as compared with genetic algorithms [9]. In standard PSO, it was commonly used for solving continuous problem. However, this study needs to consider a discrete problem to represent the position of the screws. So, a ranked-order value (ROV) algorithm, which was proposed by Liu et al. [8], should be applied. A ROV algorithm is based on random key to convert continuous data of PSO to permutations jobs for discrete particle swarm optimization (DPSO). The steps of the algorithm of DPSO were described in Fig. 2. All the models and the optimization codes were written in ANSYS parametric design language (APDL) and executed by ANSYS 11.0.

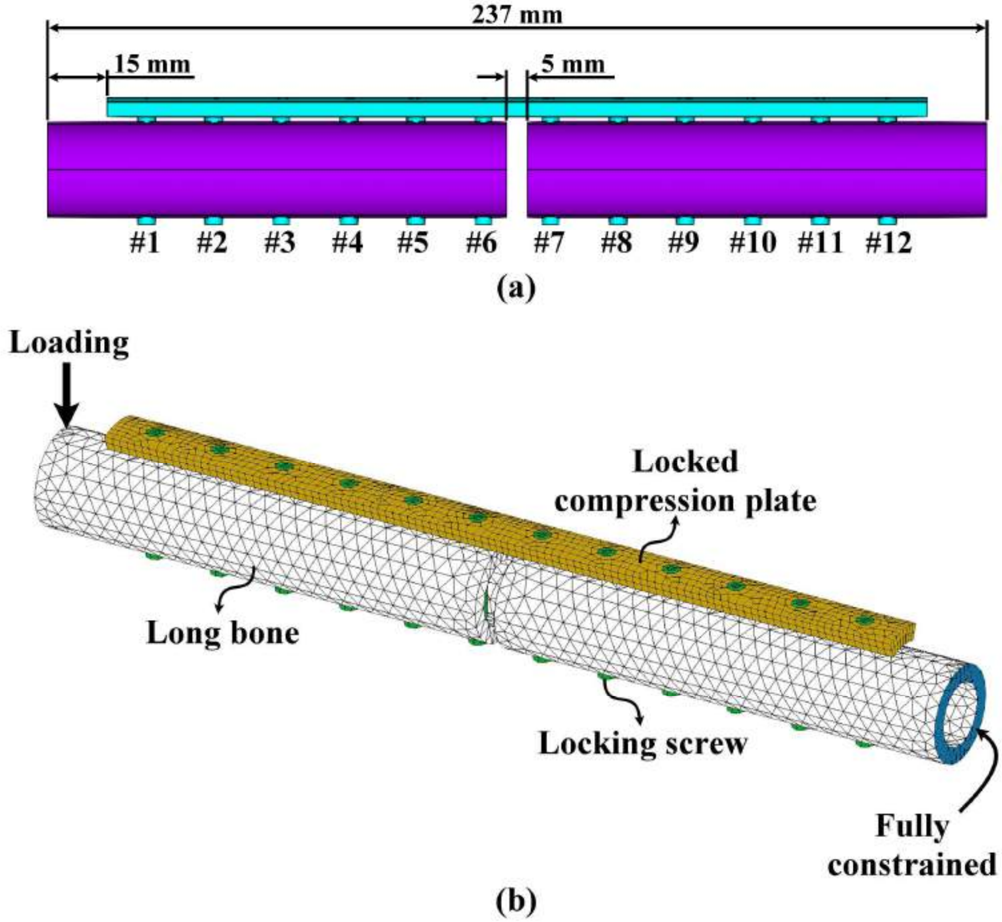


Fig. 1: The numerical models developed in this study: (a) Geometry and dimension, (b) Loading and boundary conditions.

The combinations of four, five, six, seven, eight, nine, ten, and eleven screws in twelve-hole locked compression plate were considered in this study. The numbers represent the screwís locations, 1 to 12, (Fig. 1a). The parameters between DPSO and standard PSO are quite similar. The values of cognitive and social acceleration parameters, c_1 and c_2, were kept at 2 for all the simulations. The weight factor

w was updated during iteration [7],[10] by Eqn. (1.1). The velocity-limiting factor, v_{max}, was also applied (Eq. 1.2), where k = 1. The swarm size was chosen as 10 and the maximum iteration was 100 for all the simulations (Tab. 1). The particleös velocity and location were updated by Eqn. (1.3) and Eqn. (1.4), respectively. These equations can only be used for continuous values. While updating process was complete, a ROV algorithm is then applied. Finally, an additional algorithm was added to prevent a problem when all the screws were placed in either one side of the locked compression plate.

$$w(t) = w_{upper} - \frac{t}{T}(w_{upper} - w_{lower}) \quad (1.1)$$

$$v_{max} = k \times x_{max} \quad (1.2)$$

$$\vec{v}_i(t+1) = k \times [\vec{v}_i(t) + r_1 c_1(\vec{x}_{pBest} - \vec{x}_i(t)) + r_2 c_2(\vec{x}_{gBest} - \vec{x}_i(t))] \quad (1.3)$$

$$\vec{x}_i(t+1) = \vec{x}_i(t) + \vec{v}_i(t+1) \quad (1.4)$$

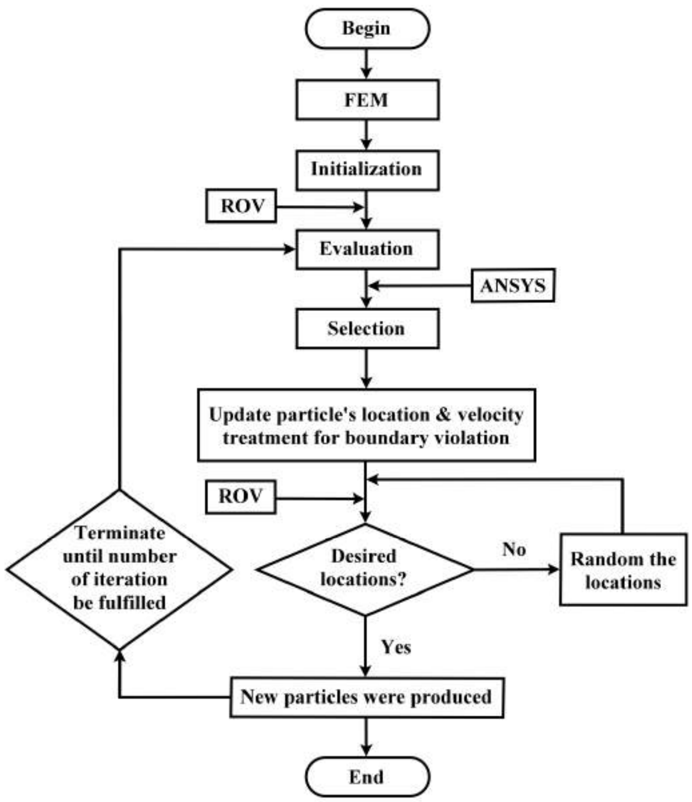


Fig. 2: DPSOös Flowchart.

Swarm size	*Max. Iteration*	c_1	c_2	w_{upper}	w_{lower}
10	100	2.0	2.0	1.0	0

Tab. 1: Strategy parameters of DPSO algorithm.

3 RESULTS

For the finite element simulation, all of the finite element models can be successfully developed and analyzed. The total number of elements varied from 9,000 to 35,000. In the convergence analysis, the maximum displacement of the numerical models converged properly. The maximum displacement for all models occurred at the tip of hollow cylinder (Fig. 3). For the optimization process, the global optimum of each situation can be accurately obtained. The detailed historical results for the combination of five screws in twelve-hole locked compression plate were shown in Fig. 4. Increasing the number of iterations could decrease the maximum displacement and increase the fixation stability.

The best configuration of the screws in each combination can be obtained (Fig. 5). Construct 5-6-7-12, Construct 5-6-7-8-12, Construct 1-5-6-7-8-12, Construct 1-5-6-7-8-11-12, Construct 1-3-5-6-7-8-11-12, Construct 1-3-5-6-7-8-10-11-12, Construct 1-3-5-6-7-8-9-10-11-12, and Construct 1-2-4-5-6-7-8-9-10-11-12 revealed the highest fixation stability in the combination of four, five, six, seven, eight, nine, ten, and eleven screws, respectively.

The maximum displacement versus the number of screws in twelve-hole locked compression plate was plotted in Fig. 6. Increasing the number of screws could significantly decrease the maximum displacement. However, a little change of the maximum displacement was found when the number of screws was greater than seven.

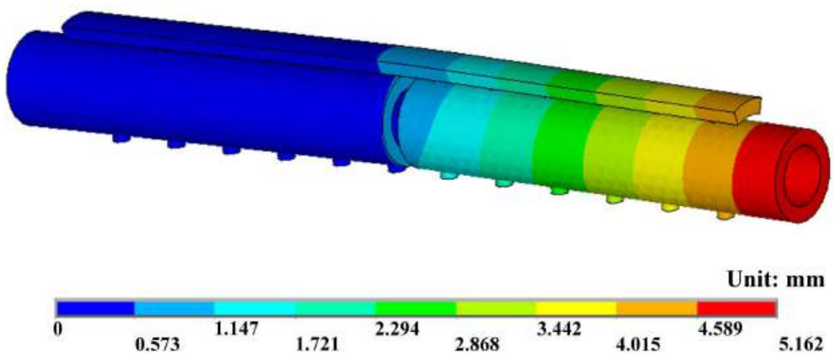


Fig. 3: Displacement distribution of the locked compression plate.

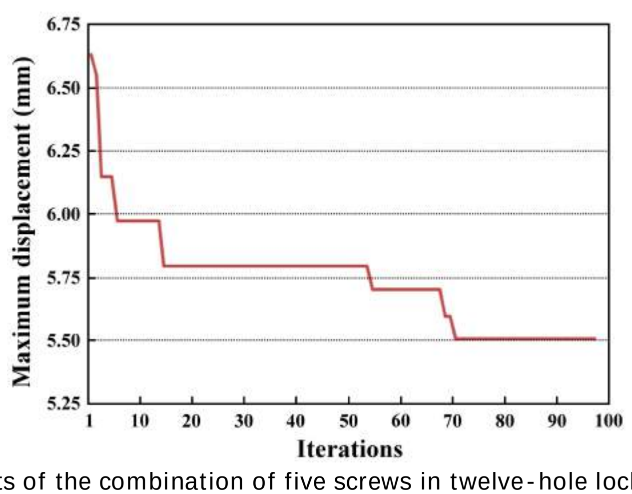


Fig. 4: Historical results of the combination of five screws in twelve-hole locked compression plate.

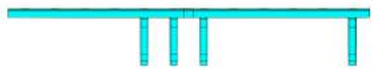
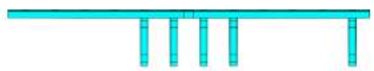
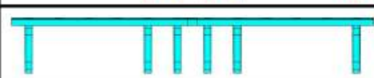
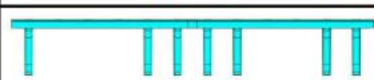
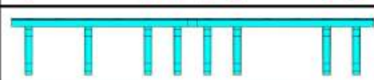
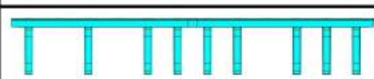
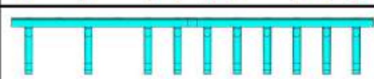
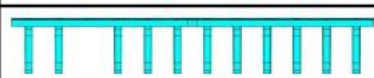
	The best screws pattern	Screw locations	Displacement (mm)
Combination of 4		5-6-7-12	5.993
Combination of 5		5-6-7-8-12	5.506
Combination of 6		1-5-6-7-8-12	5.356
Combination of 7		1-5-6-7-8-11-12	5.237
Combination of 8		1-3-5-6-7-8-11-12	5.211
Combination of 9		1-3-5-6-7-8-10-11-12	5.192
Combination of 10		1-3-5-6-7-8-9-10-11-12	5.177
Combination of 11		1-2-4-5-6-7-8-9-10-11-12	5.168

Fig. 5: The best configuration of the screws in each combination.

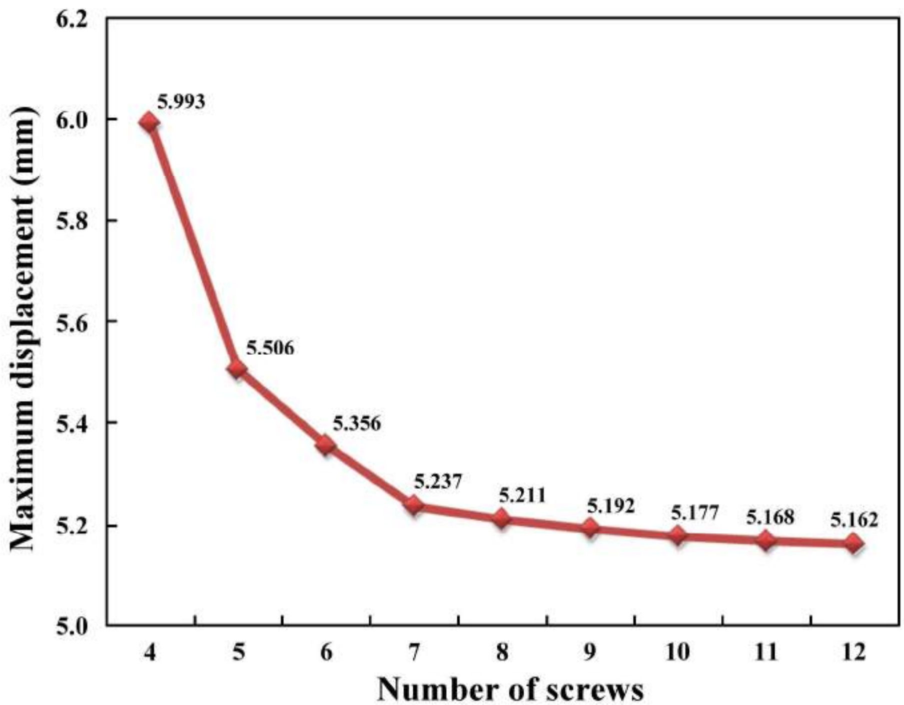


Fig. 6: The displacement versus number of screws in twelve-hole locked compression plate.

4 DISCUSSIONS

The fixation stability of the bone is an important issue in fracture healing. By minimizing the deflection of the construct, the primary bone healing can be achieved. Several commercial internal fixation plates such as dynamic compression plate, limit contact-dynamic compression plate and locked compression plate have been widely used to treat long bone fractures. Dynamic compression plates and limit contact-dynamic compression plates are contact plates which use the benefit of friction between the plate and the bone to create the compression across a fracture site. Locked compression plate is non-contact type that can provide more blood supply to the bone and allow for callus formation while still remain a great stability. Generally, a biomechanical recommendation or clinical experiences was used to assign the screws location to the plate holes but there were a lot of combinations of the screws that can be placed in numerous plate holes. In the past, there was no study investigate the best location of the screws in twelve-hole locked compression plate by using an optimization method such as DPSO corresponding to ANSYS commercial software. This study showed that the optimization program has successfully found the best locations of the screws in twelve-hole locked compression plate.

DPSO algorithm seems easy in the implementation and faster in getting the global optimum. However, this metaheuristics do not guarantee an optimal solution is ever found. The parameters of this algorithm such as c_1 and c_2, are not critical for the convergence. However, the algorithm with proper fine tuning may result in faster convergence. Those two acceleration constants are usually assumed to be 2, which was a default value for PSO [9].

In combination of four, five, and six screws, all the screws might locate in one side of the bone plate. This would cause the error during the optimization process. The additional algorithm, which can detect this problem, was applied in this study. Actually, the location of the screws would be redesigned when the error was detected. The optimal design, which has a good stability and less tissue injure, was selected by considering the smallest maximum displacement. In this study, the displacements of the combination of six, seven and eight screws are significantly different from four and five screws but the results quite close to the combination of twelve screws. From this study, six to eight screws are suggested.

Finite element method has been widely accepted as a useful method to predict and analyze mechanical behavior of some orthopedic implants under certain loading condition. The maximum displacement of twelve screws occupying the plate holes decreased by about 14 % as compared to that of four screws occupying the plate holes. However, the maximum displacement only decreased about 3.6 % for six screws occupying the plate holes. This finding was similar to that of Stoffel et al. [12]. They concluded that the locked compression plate with more than three screws did little to increase axial stiffness. Furthermore, the optimum design obtained in this study was superior to that of the past study [12]. Although the percentage difference was only less than 3 %, it was proved that the optimization program can successfully search the best location of the screws. The FEA-based DPSO is a new method that combines the advantage of FEM and well known optimization techniques. Compare to the traditional optimization tools such as PSO, DPSO, GA, etc., this new method does not need to know any fitness functions for doing optimization. The output or target values of each particle in PSO or DPSO can be provided directly by using FEM. This technique also can be applied to the other traditional optimization tools.

5 CONCLUSIONS

Stability can be achieved by increasing the number of screws and three screws on either of the segment can provide sufficient stability while minimizing the complications of plate fixation. A novel biomechanical optimization algorithm, finite element analysis-based discrete particle swarm optimization, can be considered as a new method to determine the optimum design in the biomechanical field. The results of this research could provide useful information to surgeons and help them to select the suitable screwís location and number for the patients during treatment of femoral shaft fractures.

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