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Simulation-based particle swarm optimization and mechanical validation of screw position and number for the fixation stability of a femoral locking compression plate

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ABSTRACT

Locking compression plates (LCPs) have been used to fix femoral shaft fractures. Previous studies have attempted to identify the best LCP screw positions and numbers to achieve the fixation stability. However, the determined screw positions and numbers were mainly based on the surgeons' experiences. The aim of this study was to discover the best number and positions of LCP screws to achieve acceptable fixation stability. Three-dimensional numerical models of a fractured femur with the LCP were first developed. Then, the best screw position and number of LCPs were determined by using a simulation-based particle swarm optimization algorithm. Finally, the results of the numerical study were validated by conducting biomechanical tests. The results showed that the LCP with six locking screws resulted in the necessary fixation stability, and the best combination of positions of locking screws inserted into the LCP was 1-5-6-7-8-12 (three locking screws on either side of the bone fragment with two locking screws as close as practicable to the fracture site). In addition, the numerical models and algorithms developed in this study were validated by the biomechanical tests. Both the numerical and experimental results can provide clinical suggestions to surgeons and help them to understand the biomechanics of LCP systems.

1. Introduction

Femoral fractures can be treated by inserting an intramedullary nailing system [1,2]; however, intraoperative splintering of the femur might occur during nail insertion [3,4]. Recently, a minimally invasive plate osteosynthesis technique with a locking compression plate (LCP) system has become another choice to treat femoral fracture [5–7]. LCPs, which have several locking screw holes, can allow surgeons to insert locking screws in different positions [8–10] and to use different numbers of locking screws [11,12]. In clinical application, an LCP with a small number of locking screws can reduce the bone and soft tissue damage, but an LCP with a large number of locking screws can enhance fixation stability. Fixation stability is important to the success rate of fracture healing [13–15]. To achieve the necessary fixation stability, previous studies have investigated the proper screw positions and numbers by applying numerical methods and/or experimental methods [8–12,16,17]. However, the LCP screw positions and numbers were mainly determined according to the surgeons' or researchers' prior experience [18,19]. In the present study, three-dimensional finite element models were first developed to analyze the fixation stability of LCP systems. Then, a simulation-based particle swarm optimization algorithm was developed and applied to find the optimum position and number of locking screws. Finally, LCP systems were manufactured, inserted into synthetic femurs, and tested to validate the results of the numerical models and engineering algorithms. The purpose of this study was to apply the simulation-based particle swarm optimization algorithm and biomechanical tests to discover optimum screw positions and numbers for LCP systems to achieve acceptable fixation stability.

2. Materials and methods

2.1. Numerical models of the femur with an LCP system

Three-dimensional solid models consisted of a femur, a twelve-hole LCP, and locking screws. The femur model, which consisted

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of cortical bone and cancellous bone, was created according to the computed tomography scanning image of one healthy male volunteer. In addition, a transverse femoral shaft fracture with a fracture gap of 5 mm was assumed and developed. The LCP was developed, and its dimensions were 210 mm in length, 18 mm in width, and 6 mm in thickness. All of the locking screws were assumed to be 4.5 mm-diameter cylinders. The length of the locking screws ranged from 30 to 40 mm. The LCP system was inserted into the fractured femur and the LCP was in contact with the femur. The solid models and the finite element models were created and analyzed with ANSYS 12 (ANSYS, Inc., Canonsburg, PA, USA). The linear elastic isotropic materials were assumed and assigned for both the femur and the LCP system. For the material properties of the femur, the Young's modulus was 17 GPa for the cortical bone and 0.32 GPa for the cancellous bone. The Poisson's ratio of both the cortical and cancellous bone was 0.3 [20]. For the material properties of the LCP system, the Young's modulus and the Poisson's ratio were 210 GPa and 0.3, respectively. To decrease the computational time, the absence of the locking screws was simulated by adjusting their Young's modulus to 0.01 GPa. The femur and the locking screws were free-meshed and the LCP was map-meshed with the use of high-order 20-node elements of SOLID 95. A convergence analysis was conducted to avoid inaccurate outcomes caused by improper element size. In the interface condition, the interfaces between the LCP and the locking screws were bonded because of the locking screw hole design. The interfaces between the femur and the locking screws were also bonded because the screw is threaded into the femur. The interfaces between the LCP and the fractured femur were contact. In the loading condition, the hip-joint force and the gluteal medius muscle force were applied to simulate the loading from a single-leg stance (Table 1) [20,21]. In the boundary condition, all degrees of freedom at the distal end of the femur were fully restrained (Fig. 1A). In the post-processing, the maximum displacement in the superior-inferior direction was calculated to evaluate the fixation stability of the fractured femur with the LCP system. Thus, the maximum displacement ($F_{displacement}$) was selected as an objective value for this optimization study.

2.2. Definitions of design variables and constraints

Design variables and constraints are required for design optimization problems. In the current study, the design variables were the locking screws which were either present in or absent from the LCP. Thus, twelve design variables (From DV_1 to DV_{12}) were defined because a twelve-hole LCP system was used in this study (Fig. 1B). Each design variable was continuous, and the design range was from zero to one. However, to determine the best screw positions, the design variables were ranked according to their values. Thus, a design variable with higher ranking had higher priority to be selected. Therefore, a design variable value approached one if this position required the insertion of a locking screw, and it approached zero if the position did not require the insertion of a locking screw (Fig. 2A). To convert a continuous value, a ranked-order value algorithm [22] was applied to obtain a ranking of all design variables in this study. The constraints of the optimization problem included the number of locking screws used in the LCP (N_{screw}), the number of locking screws inserted into the proximal fragment ($N_{proximal}$), and the number of locking screws inserted into the distal fragment

Table 1
The loading conditions used in the numerical models.

	Hip-joint force (N)	Muscle force (N)
X-direction (medial–lateral)	320	−310
Y-direction (anterior–posterior)	170	0
Z-direction (superior–inferior)	2850	−1200

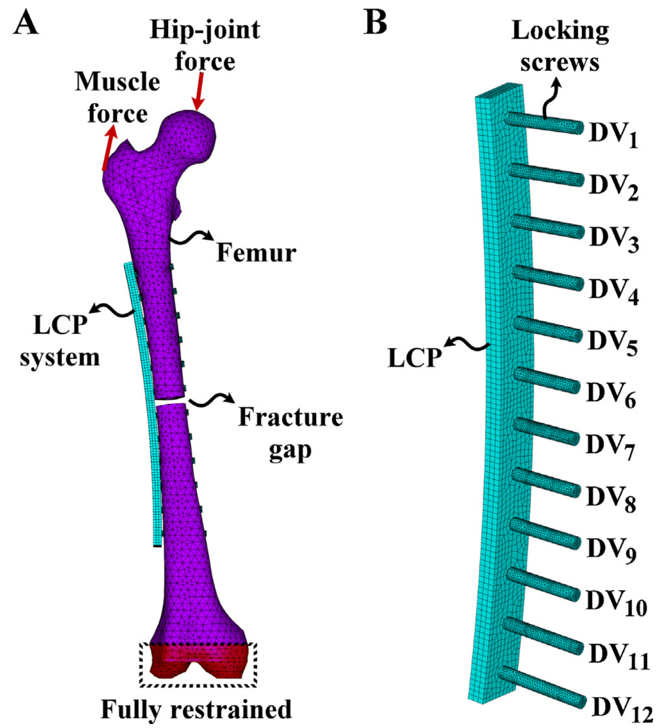

Fig. 1. (A) The loading and boundary conditions of the numerical models. (B) The design variables of the LCP system.

(N_{distal}). For N_{screw}, four, five, six, seven, eight, nine, ten, and eleven locking screws, which were inserted into the LCP, were considered to present the best screw positions. To avoid the insertion of all locking screws into only one bone fragment, $N_{proximal}$ and N_{distal} should be equal to or greater than one. This designation meant that at least one locking screw should be inserted into the proximal fragment and into the distal fragment. However, the $N_{proximal}$ and N_{distal} constraints are unnecessary if N_{screw} is equal to or greater than seven (Fig. 2B).

2.3. Optimization of screw position and number

An optimization problem consists of an objective function, design variables, and constraints. In this study, the objective function was to minimize the maximum displacement of the fractured femur with the LCP system. The design variables were the locking screws, which were inserted or omitted. The constraints were the number of locking screws used in the LCP, the number of locking screws inserted into the proximal fragment, and the number of locking screws inserted into the distal fragment. Thus, the design optimization problem studied here could be summarized as follows:

$$\text{Minimize}: F_{displacement} = f(DV_1, DV_2, \ldots, DV_{12})$$

$$\text{Subject to}: \begin{array}{l} N_{screw} = 4, 5, 6, 7, 8, 9, 10 \text{ or } 11 \\ N_{proximal} \geqq 1 \text{ and } N_{distal} \geqq 1 \text{ (these can be ignored if } N_{screw} \geqq 7) \\ 0 \leqq DV_i \quad i = 1, 2, 3, \ldots, 12 \end{array}$$

To discover the best screw positions and numbers, a particle swarm optimization algorithm, which was originally developed by Kennedy and Eberhart [23], was applied. Particle swarm optimization is an evolutionary computational and population-based stochastic optimization technique, and it is inspired by the behavior of fish schooling or birds flocking. A particle is like a "fish" or "bird" in a search space, and all particles have fitness values and