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ORIGINAL ARTICLE

Schematization of Cannulated Screw Fixations in Femoral Neck Fractures Using Genetic Algorithm and Finite Element Method

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Abstract

Purpose Femoral neck fracture (FNF) is one of the most observed orthopedic injuries in elderly patients with accompanying osteoporosis, while treatment process could be highly troublesome in young patients. Therefore, it is necessary to apply a strong fixation to the FNFs. This study aims to suggest an approach for the optimum screw design for FNFs using genetic algorithm (GA) and finite element method (FEM) in a seriously shorter time, considering that a very large number for the design of the implants comes forward that would take a lifetime to solve individually.

Methods In biomechanical studies conducted under laboratory conditions and focusing on stabilization, limited number of combinations have been tested with limited materials by now. However, ideal position, size and number of the screws are still subject of discussion. Unlike previous biomechanical studies; the present study addresses three types of CSFs (binary screw, triple screw and quadruple screw), while aiming to determine the optimum position, size and number of the screws using a design approach based on GA and FEM.

Results This study emphasizes that screw configuration plays an important role on the treatment process of the femur. As a result of all evaluations and analyses, the most effective designs have been achieved for binary, triple and quadruple screw patterns.

Conclusion In this study, all of the possible combinations and screw sizes have been evaluated to determine the optimum conditions for fracture stability. Suggested design approach could be used more effectively by healthcare disciplines such as orthopedics, in which biomechanical principles are significant. Moreover, cooperation between structural and biomechanical engineering is another remarkable eligibility of this research.

Keywords Femoral neck fractures · Internal fixation implants · Screw configuration · Optimum design · Genetic algorithm · Finite element method

1 Introduction

Although the number of femoral neck fractures (FNF) varies with age, sex, and region, this fracture type is one of the most important and challenging health problems all around the world. Regarding the treatment of FNFs, multiple screw installation is the most preferred stabilization method since the method is a minimally invasive method with percutaneous application after closed reduction, which shortens the duration of surgery and does not lead to bleeding. The main purpose of the screws is to ensure that the fracture heals quickly and to provide daily activities safely. Size, location and length of the screws are the most effective parameters in terms of structural performance of internal fixation implants (IFIs). Therefore, the application of the most appropriate configuration is of great importance for FNFs. However, in

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case of the preference of IFIs for the treatment of FNFs, those screws are often placed considering widely accepted principles. Fixation is most often carried out with 3 screws in the form of inverted triangles. During the operation, surgeon aims to place the distal screw nearby the inferior cortex, and proximal screws nearby the anterior and posterior cortexes. It is undesirable to orientate the screws nearby to the central. Considering that, it is obvious that there is a very large number of possibilities for the placement of the screws.

Cannulated screws are surely among the most remarkable and popular internal fixation implants. Recently, treatment of FNFs with multiple cannulated screws has gained the interest of many researchers and orthopedists based on many aspects of their unique properties. Inappropriate treatment of FNFs might lead to serious complications such as avascular necrosis at the femoral head or failure of bone union; could even require arthroplasty for young patients. Depending on these facts; it might lead to undesirable and non-reversible situations such as joint replacement at early ages. For this reason, it is very important that the screws used in FNFs are correctly selected and applied.

Femoral neck fractures should be approached using a proper method owing to the anatomical and biomechanical characteristics of the fracture. Especially configuration of the fracture should be considered while the action of various groups of muscles on the hip is another significant factor not to be neglected for the handling of a femoral neck fracture. Thus, accurate application of internal fixations is a mandatory requirement for the successful treatment and healing of the fracture [1]. Throughout the previous research, several biomechanical studies have demonstrated that multiple screws are mainly used for internal fixation. Sensoz et al. [2] has suggested a screw design approach considering the risk of iatrogenic subtrochanteric fracture using finite element method. Apart from this, it has generally been shown that there is no precise design configuration for the screws [3–6]. Moreover, limited studies have focused on different implementation configurations and orientations of the screws. Therefore, this study aims to suggest an approach for the optimum screw details for FNFs using GA method. In order to better understand the optimum screw configuration, three types of cannulated screw fixation (CSF) examples; binary screw (S2), triple screw (S3) and quadruple screw (S4) were investigated and analyzed. The study also emphasizes the importance of interdisciplinary relations, and it is evaluated that the integration, association and incorporation between structural engineering and medical sciences make it possible to increase the importance and widespread effects of the research.

2 Methodology of the Genetic Algorithms

Genetic algorithms (GAs) are based on an adaptive heuristic search approach that is established on genetic evolution mechanism [7, 8] and aims to mimic natural evolution processes. Main point of this method is the principle of survival of the fittest and adaptation to the current conditions. When a population of biological species evolves over generations, future generations receive positive characteristics required for survival from the older ones, because individuals carrying them get more chances to breed owing to the evolutionary ideas of natural selection [9]. In other words, competition among individuals for limited resources leads to the fittest individuals to survive by dominating over the weaker ones [10]. Although the genetic algorithm is a search method that is guided to find the best by specific criteria, it is not a guarantee that it will find the best solution. However, previous studies have shown that most of the optimization applications performed with genetic algorithms are more efficient than the results obtained with other optimization methods in terms of applicability [11]. Unlike conventional artificial intelligence systems, GAs do not fail easily despite the presence of slight input alteration or reasonable data noise.

In GAs, a population of possible solutions to the given problem are identified initially and then, acquired solutions are evaluated within recombination and mutation techniques by imitating development of natural genetics. Therefore, this process is repeated over various generations by continuously producing new children. A genetic algorithm starts with an initial generation, which consists of possible solutions represented by character strings encoded by design variables. Each generation consists of a population of character strings, which resembles the structure of a chromosome that constitutes the DNA of living creatures. Each individual represents a point in a search space which is a possible solution. Discrete design variables are used in GAs and the values that these design variables can take are determined before the search starts. Coding of the design variables in the character strings is implemented in the form of coding the sequence number in the design variable set. The sequence number can be encoded in binary or triple number system as well as in real value. If the most common binary number system is used, the character strings consist of "1" and "0". In this approach, it is possible to associate the clusters formed by the character strings to population, the character strings to individuals (chromosomes), and numbers in the character strings to genes.

The GA method has a case dependent structure and appropriate selection of the key parameters is essential for the successful development and an acceptable performance

[12]. These key parameters include parent selection method, crossover type and rate, mutation rate, survivor selection method and number of individuals. In particular, it is known that it gives very good results in design and it is applied in disciplines such as automatic programming, learning machines, economics, planning and production line settlement [13]. For almost all of these problems, a very large solution space needs to be defined. Although this solution might take a longer time in some situations to be investigated with conventional methods, GAs can find optimal or near-optimal solutions to difficult problems in a shorter time [14].

3 Determination of the Implant Design via Genetic Algorithm

The GA approach has had several applications in various collaborative studies of engineering and orthopedics disciplines. However, there has been no research on the optimum design of internal fixation implants for FNFs considering binary screw (S2), triple screw (S3) and quadruple screw (S4) designs. This study focuses on the FNF of 40° inclination angle from the horizontal line, which is commonly encountered. Figure 1 demonstrates the possible locations of the implants at the fracture plane, being numbered and marked with yellow circles. In order to designate the implant installation for the fracture, diameter and inclination of the implants should be specified carefully for the purpose of a successful treatment. Therefore, a very large number for the design of the implants comes forward that would take a lifetime to solve individually.

In fact, the most preferred screw fixation models for femoral neck fractures are; (i) using three parallel screws (reverse triangle configuration in side view—two screws in upper portion of the head, one in lower portion of the head), and (ii) four parallel screws (rectangular model). Although it is not a favored current clinical model, design approach in this study is not limited with parallel placement of screws in order to lead further alternatives. The outcomes of the proposed approach should principally be evaluated from the point of digital model rather than anatomic and clinical situations.

Because of the complexity of the femur structure, optimization process should be handled meticulously. Furthermore, for the purpose of simulating the screws to function properly and congruously with the bone material throughout finite element analysis, total harmony is required between genetic algorithm and numerical analysis. Hence, the GA process has been coded in MATLAB software without the toolbox option in order to maintain an iterative optimization procedure that works simultaneously with ANSYS software. Additionally, within the context of the procedure, genetic operators have been selected as in Table 1, while defined

Table 1 Genetic operators and operation parameters

Parent selection operator	Fitness proportionate selection
Reproduction rate	0.5
Crossover operator	Uniform crossover
Crossover rate	1.0
Mutation operator	Random resetting mutation
Mutation rate	0.02
Survivor selection operator	Fitness based selection

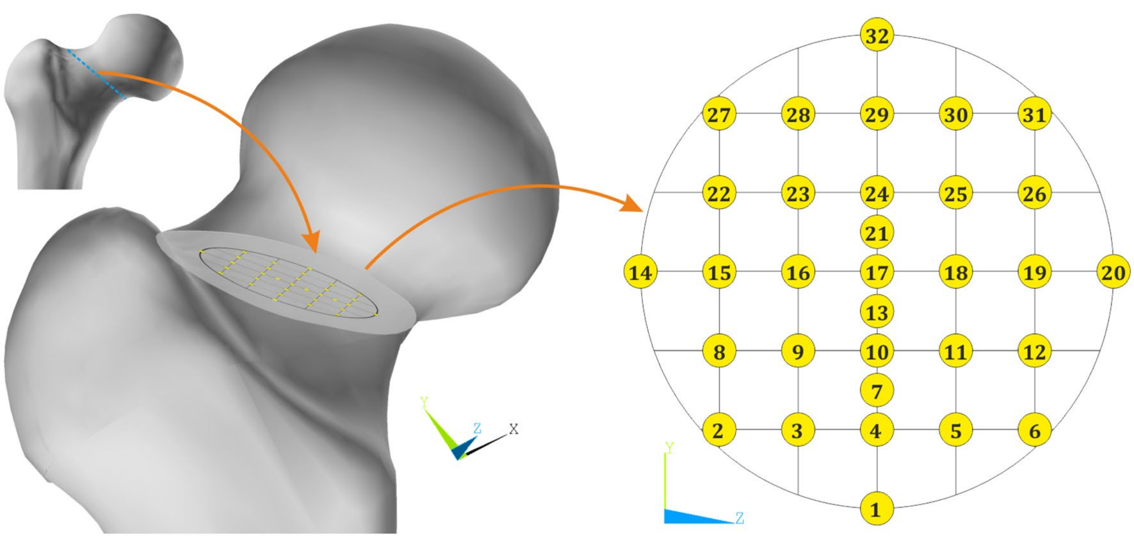

Fig. 1 FNF of 40° inclination angle and possible implant locations

Table 2 Design variables of the GA

	Variable range	Variable count	Bit count
Implant diameter	3.50–8.00 mm	2^4 (16)	4
Implant location	32 points on the fracture plane	2^5 (32)	5
Inclination from *xy* plane	(− 10°)–(+ 25°)	2^3 (8)	3
Inclination from *xz* plane	(− 20)°–(+ 55°)	2^4 (16)	4

ranges and counts for the design variables are presented in Table 2.

In order to elaborate the selection of genetic operators and parameters, some explanations could be useful. It is a fact that values of genetic operators are regarded as problem dependent. The essential aim of selection strategy is "the better is an individual; the higher is its chance of being a parent" [15]. Fitness proportionate selection, which is also called as roulette wheel selection, has been determined as the parent selection operator to assign the individuals their probability of selection based on the fitness values for the subsequent parent selection. Each parent candidate is assigned a slice of a circular "roulette wheel" and the size of this slice is proportional to the candidate's fitness. The wheel is spun *N* times, where *N* is the number of individuals in the population. On each spin, the individual under the wheel's marker is selected to be in the pool of parents for the next generation [16]. This *N* parameter depends on the reproduction rate, which specifies how many of the population are assigned as parents and the rest is eliminated. These parents are coupled with each other and new individuals (offspring) are reproduced from them using crossover operator. Uniform crossover operator generates a random pattern, and bits in the parent chromosomes are swapped based on this pattern. Crossover rate, which is in the range of [0, 1], is the number of swapping that two chromosomes exchange their bits. 100% crossover rate means that all offspring are produced by the crossover process while 0% means that all of the new generation is totally copied from the individuals of older population, except those resulted from the mutation process [17]. Following the crossover process, mutation operator is applied in order to prevent the algorithm from converging to local optima and giving chance to produce distinct genes in the new generation [18]. In case the chromosomes in any generation represent high similarity, evolution of the offspring gets almost impossible. This phenomenon, which is called premature convergence is prevented by the mutation process [19]. Mutation rate determines how many chromosome bits in the whole population should be mutated in one generation by being flipped (0 becomes 1, 1 becomes 0), and typically is in the range of [0.001–0.1]. If it is too low, possible good genes could be never tried out. If it is too high, there will be much random disorder, the offspring will start losing their resemblance to the parents, and the algorithm will lose the ability to learn from the history of the search [20].

The effectiveness of GAs relays on the selection of its control parameters (population size, crossover, and mutation) that interact in a complex way [18, 21–23]. Since no precise values could be specified for each parameter in a design search problem, particularly, mutation and crossover operators [18]; these parameters have been decided by trial and error subsequent to former trial processes for the purpose of performing a reliable optimum design search by considering the suggestions in the previous studies. Using predefined ranges for the design variables; initial population size values are 100, 200 and 400, while 2^{32}, 2^{48} and 2^{64} possible designs are applicable for S2, S3 and S4 patterns, respectively. Superscript of the possibility number also indicates the chromosome length. As it is seen in Table 2, each of the design variables have a variable range and count. Design of a screw is determined by four variables, which could be called as genes. 16 bits in a chromosome represent a screw design. For the S4 design, a chromosome has a total of 64 bits. GA process is terminated after 50 generations for all of the screw installation patterns, which means that optimum solution is reached by 50 generations. For the purpose of deciding the limit of generation number, former trial processes revealed that fitness value of the best design in a generation do not remarkably increase after the 50th generation for all of the problems in this study. Considering the initial step of the genetic search, Goldberg [24] suggested that optimal population size could be calculated as $1.65 \cdot 2^{0.21 \cdot l}$, where l is the length of a chromosome. Nevertheless, the optimal population size revealed by this formula is out of the computational possibilities for most practical problems [25]. This formula yields reasonable values for the size of panmictic populations but unreasonable high values for parallel evaluation approaches, since it only considers the randomly constitution of a population [26]. However, this study focuses on the design of screws, which are interdependent and also depend on the geometry of the femur bone. For this purpose, an initial control is performed before constitution of the first population and this control is maintained for all of the next generations.

Prior to the initialization of the GA, a preparative design process has been carried out. It is known that bone is insufficient against rotational displacement in the treatment of fracture using single screw in the treatment of femoral neck fractures. Hence, the use of multiple screws is recommended for femoral neck fracture treatments. It is very important to provide implant stability at the stage of multi-screw application and to perform a rotation resistant application by obtaining dynamic internal fixation. Therefore, it is necessary to correctly determine the position of the screws to be used in the front, back and side radiographs. The proper position of the screw at the femoral head has been the subject of intense debate. In general, deep and central placement of the screw is recommended in both anteroposterior and lateral plans. Some authors advocate the position of the screw in the middle in the lateral plane, close to the femoral in the AP plan. Some studies recommend the posteroinferior quadrant of the head in the lateral plane, and its low placement towards the lifted femorale in the anteroposterior plane, in order to provide sufficient bone support stock within the osteoporotic bone structure. However, there are publications suggesting that eccentric placement will have difficulty in providing rotational stability. Today, the position of screws is usually determined by the surgeon performing the surgical intervention, taking into account different approaches such as Garden Alignment Index, Lowell's Alignment Theory, Tip Apex Distance and Parker's ratio. Essentially, it is known that installation of screws distant to the calcar and posterior cortex, decreases the stability and increases the complication chance in terms of fixation of FNFs [27, 28]. Variable ranges of screw inclinations have been determined based on this consideration. Additionally, some of the initially estimated designs have the possibility of screws to intersect with each other and initial population should be created by avoiding this undesirable situation. Hence, all of the initial designs are checked within the algorithm using a mathematical function regarding the positioning of the screws. If any screw intersection is found among the population members, they are replaced by applicable designs throughout the optimization algorithm. This process also enriches the diversity of the population. It should also be noted that, intersection of the screws might be met for some of the offspring in the next generations. Because mathematical check requires significantly shorter computation time, fitness values of these offspring are directly assigned to zero and they are excluded from the finite element analysis (FEA).

Following this preliminary stage, GA is started and optimum implant schema is sought over iterative generations. Because success of the GA depends essentially on the identification of numerical performance of designs; an objective function, which is called fitness value, should be defined. All the optimization methods fundamentally ask the same question: "Which one of the optimized designs is the best or what is the optimality level?" [29]. Since each of the design parameters causes distinct designs, a performance qualification method is required to be constituted subsequent to the definition of all the design criterions [30, 31]. It is well known that hip joint and trochanteric region resemble a region where static and dynamic forces are combined and dispersed during standing and walking positions. According to Pauwells, there is an equal load distribution on both hips and the load on each hip is half the weight of the body while standing in a static position [32]. When walking or running, the load on each hip varies. Therefore, these static and dynamic loads on the hips cause different types of stresses and displacements in the femur. For this reason, this study focuses on the critical stresses and displacements that occur in both bone and screws. Considering that displacement and stress values in femur bone and implants should be decreased to prevent a secondary damage, also selection of implants with smaller cross-sectional area would be better in terms of protecting the unity of femur bone; following function was formulated in order to define the fitness of chromosomes as an optimality criteria. Previous studies on cannulated screw fixation methods consider just one performance output; stress level of screws or displacement in the fracture. Although this formulation could be regarded as an intuitive approach, further improvement is possible by considering different design criteria.

$$\max(f) = \left(\frac{u^{lim}_{femur}}{u^{max}_{femur}} + \frac{\sigma^{lim}_{femur}}{\sigma^{max}_{femur}} + \frac{\sigma^{lim}_{screw}}{\sigma^{max}_{screw}} + \frac{A^{lim}_{screw}}{A^{total}_{screw}} \right) / 4 \quad (1)$$

In Eq. (1); u^{max}_{femur} is the maximum displacement value of the femur head, σ^{max}_{femur} is the maximum von Mises stress in the femur bone, σ^{max}_{screw} is the maximum von Mises stress in the screw material and A^{total}_{screw} is the total cross-sectional area of the screws; while u^{lim}_{femur}, σ^{lim}_{femur}, $\sigma^{lim}_{screw}\sigma^{lim}_{screw}$ and A^{lim}_{screw} are the constant limit values for those, which are defined by considering material and design characteristics.

It is a known fact that GAs have the potential to yield different results even if genetic operators and parameters are the same for all of the processes. Hence, several optimization processes have been performed in order to achieve different implant designs. Throughout the examination of yielded results from each of the GA processes; implant designs, which are evaluated to be more advisable in terms of the applicability, were selected within the presentation of this study to emphasize the efficiency of the proposed method. Three configurations in S2, two configurations in S3 and two configurations in S4 implant patterns were presented herein. Required screw diameters according to the results of the GA processes are 5.00 mm, 4.00 mm and 3.50 mm for S2, S3 and S4 patterns, respectively. Locations, inclination angles and number of the screws achieved by the GA processes are presented in Tables 3, 4 and 5 (implant locations are indicated by numbers on the fracture plane) and also demonstrated on the fracture plane in Figs. 2, 3 and 4, respectively.

Table 3 Design details of binary screw installations

Implant no.	S2A		S2B		S2C	
	1	2	1	2	1	2
Implant diameter	5.00 mm		5.00 mm		5.00 mm	
Implant location	29	1	26	22	29	1
Inclination from *xy* plane	− 5°	+ 15°	0°	+ 10°	− 10°	+ 10°
Inclination from *xz* plane	+ 40°	+ 20°	+ 20°	+ 40°	+ 10°	− 5°

Table 4 Design details of triple screw installations

Implant no.	S3A			S3B		
	1	2	3	1	2	3
Implant diameter	4.00 mm			4.00 mm		
Implant location	2	32	20	32	12	8
Inclination from *xy* plane	+ 5°	+ 15°	− 5°	0°	0°	+ 10°
Inclination from *xz* plane	− 5°	+ 10°	+ 45°	+ 35°	+ 30°	+ 45°

Table 5 Design details of quadruple screw installations

Implant no.	S4A				S4B			
	1	2	3	4	1	2	3	4
Implant diameter	3.50 mm				3.50 mm			
Implant location	14	32	12	2	27	31	2	6
Inclination from *xy* plane	+ 5°	+ 5°	+ 5°	+ 5°	+ 5°	− 5°	0°	0°
Inclination from *xz* plane	+ 10°	+ 20°	+ 5°	+ 15°	+ 15°	+ 30°	+ 45°	+ 45°

4 Validation of the Implant Design Via Finite Element Analysis

Main objective of finite element analysis (FEA) is to predict the deformation, strain or stress distributions in a body subjected to various forces. Finite element models of the implants were validated by computational analyses using ANSYS software. It is quite difficult to precisely determine the material properties of the femur bone to be used in the analyses. Therefore, in this study, mechanical properties were determined by taking previous studies into consideration, and some general assumptions were made because of the complexity involved in the osseous structure [33–39]. In the numerical models, mechanical characteristics were determined to be compatible with the previous studies. Young's modulus, Poisson's ratio, unit weight values for the bone and screw materials were assumed to be 15 GPa and 193 GPa, 0.30 and 0.31, and 0.55 and 7.75 g/cm^3, respectively. Due to the expected interaction of the bone parts on the fracture surface, the coefficient of friction was assumed to be 0.3 and a fully bonded connection was considered between the bone and screws in these models. This approach has been accepted and applied within many studies [40–46]. Therefore, in this study, finite element analyses were carried out taking this assumption into account.

Additionally, regarding the loading conditions, femur head was subjected to a vertical load of 1000 N. Given that forces on each human hip can increase up to 2–3 times of body weight, load level was assumed to be adequate by applying a maximal force of 1000 N to the femur head (i.e., two times of the body weight of a 100 kg person or three times of the body weight of a 67 kg person). Moreover, when previous research on femoral neck fractures are examined, use of a 1000 N vertical load has been generally preferred in finite element analyses [47–49]. In the boundary conditions, design models were considered as fully restrained at the base of the femur shaft.

Since this research considers the possible risk of very small deformations on the fracture surface, it is assumed that there is a linear relationship between loading and deformation. In the case that deformations have higher values, integrity of the treated bone region would be deteriorated. Objective of a structural linear analysis is accurately interpreting the formation of stress distribution and damage at initial load levels. Since the overall behavior of a structure before significant deformation has utmost importance, linear elastic material behavior was considered by ignoring stiffness degradation for the analysis of the implant models. Computation time for a finite element analysis is less than 30 s while many of the individuals created within the genetic search algorithm violate the

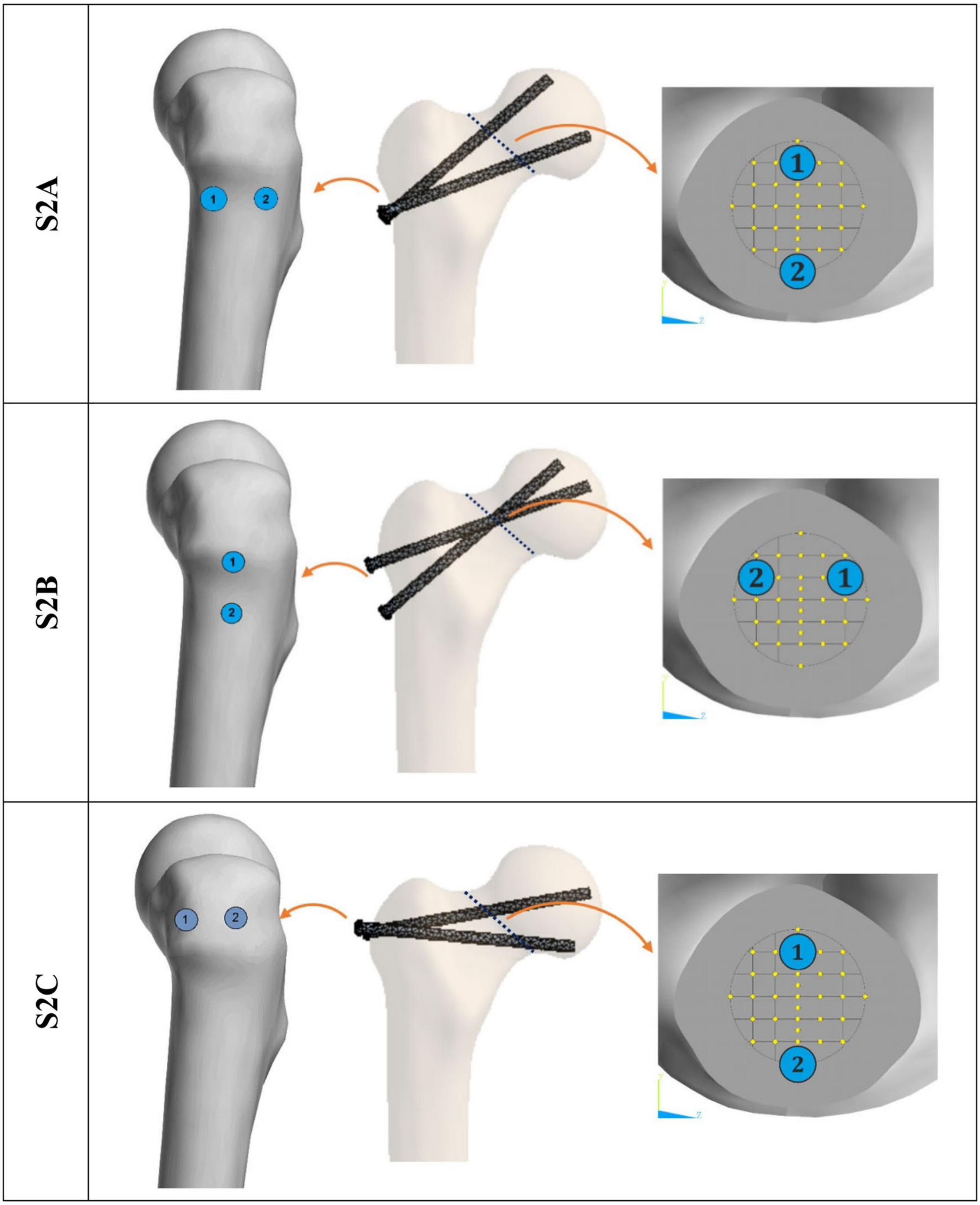

Fig. 2 Design details of implant installation with two screws

prescribed design limits. As mentioned before, these limits depend on the positioning of the screws and geometry of the femur bone. Thus, invalid screw designs, which are determined by a mathematical function, are not subjected to FEA and eliminated directly within the algorithm. Complete optimization process takes about 5, 10 and 20 h for S2, S3 and S4 designs, respectively.

Throughout the generation of finite element models, femur and screws were meshed by using tetrahedral SOLID186 elements which are defined by 10 nodes and having three degrees of freedom at each node (translations in the nodal X, Y and Z directions). Element type was selected from the ANSYS library. Finite element models of the implant designs were meshed by defining 65,000–88,000

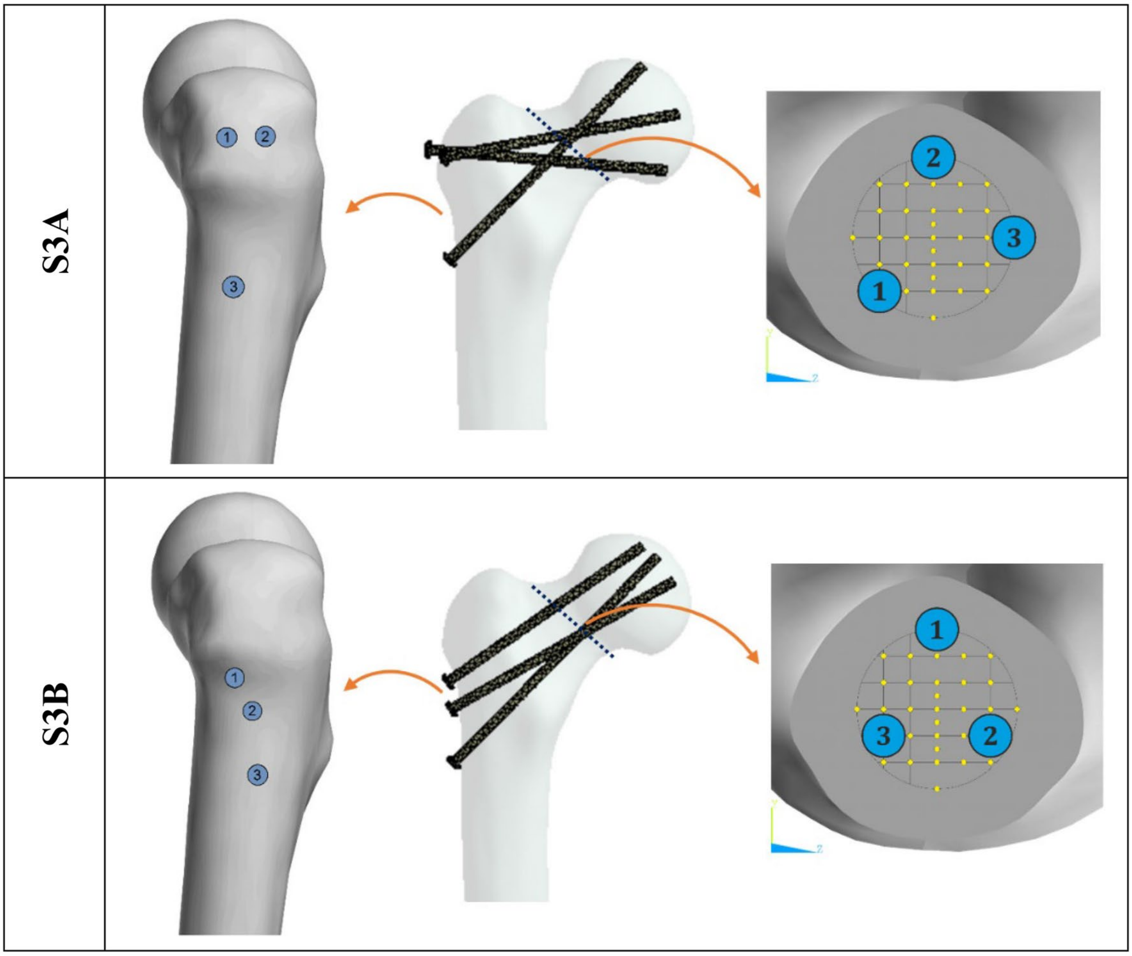

Fig. 3 Design details of implant installation with three screws

nodes and 42,000–57,000 elements as illustrated in Fig. 5. Prior to the finite element analysis, mesh convergence analysis was performed to determine the appropriate mesh number and mesh quality. For the convergence plot, the maximum allowable change was considered as 5% and total number of nodes and elements for the optimized designs are given in Table 6.

5 Results and Discussion

Within the scope of this study, three types of CSFs, namely S2, S3 and S4 patterns, are investigated through the genetic algorithm (GA) and finite element method (FEM). All of the numerical results of the femur bone and the screws, obtained from the finite element analyses of each configuration are summarized in Tables 7 and 8.

Regarding the total deformation results of the femur in Table 7, observed lowest value is 14.24 mm in the S4B while the highest value is 14.47 mm in the S3A. Despite the variation of total deformation results, these differences are insignificant in proportion. On the other hand, considering critical stresses over von Mises yield criterion, the lowest stress is 22.29 MPa in the S2B while the highest stress is 32.12 MPa in the S4B. The difference between the lowest and highest stress levels is approximately 30%, which is significant compared to the total deformation variation. Moreover, the lowest values of maximum principal stress, minimum principal stress and maximum shear stress are 34.73 MPa in the S2B, 35.33 MPa in the S3B, and 2.71 MPa in the S2B and the highest values of those are 42.87 MPa in the S2A, 50.33 MPa in the S2C, and 5.04 MPa in the S4B, respectively.

The results in Table 8 show that the lowest value of deformation on the screws is 13.44 mm in the S2C while the highest value is 14.25 in the S3A. Maximum von Mises stress values on the screws vary between 196.00 MPa (in the S2A) and 237.52 MPa (in the S3B). In addition, the lowest values of maximum principal stress, minimum principal stress and maximum shear stress are 191.41 MPa in

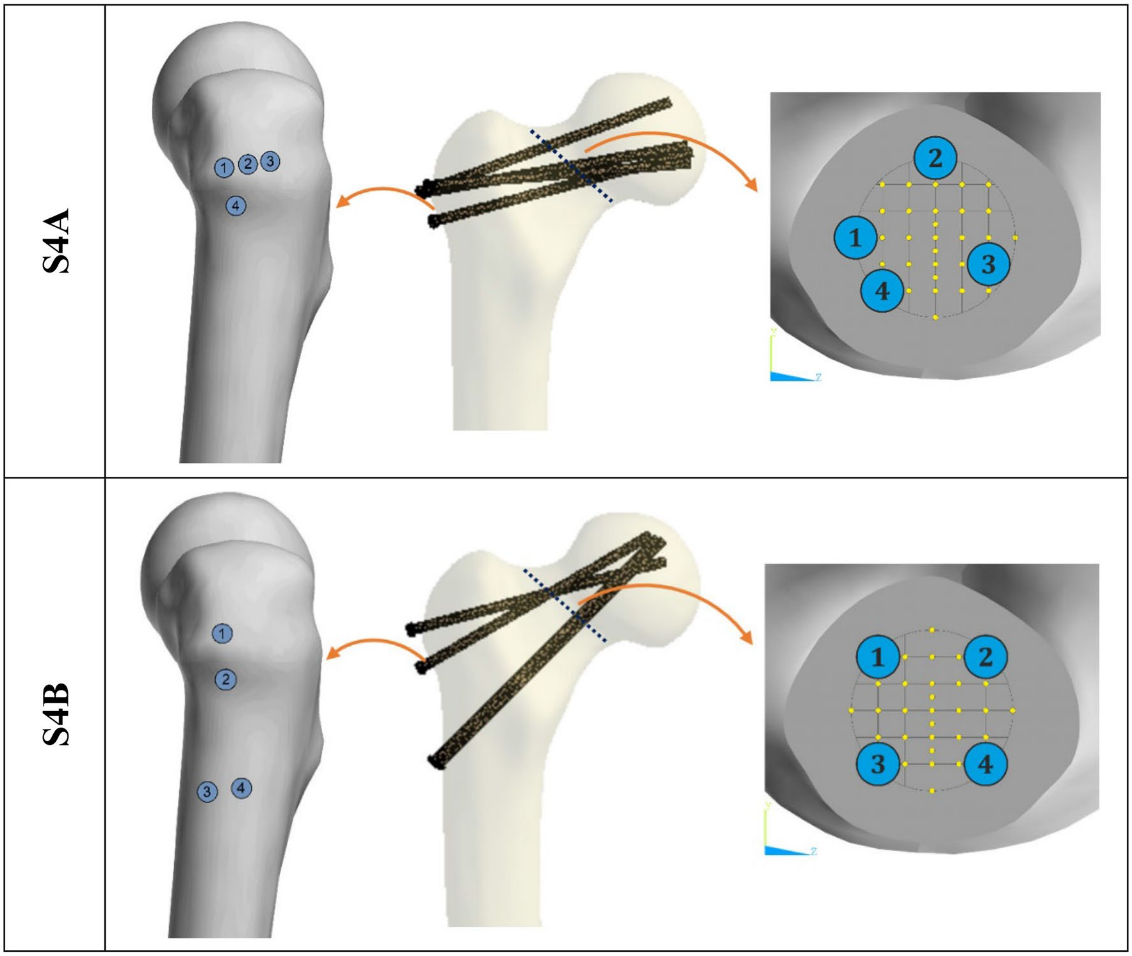

Fig. 4 Design details of implant installation with four screws

the S2A, 168.40 MPa in the S2B, and 10.59 MPa in the S4A and the highest values of those are 238.98 MPa in the S3B, 199.54 MPa in the S3A, and 33.91 MPa in the S2A, respectively.

Overall, in order to determine the optimum configuration for all of the screw designs, fitness values are calculated and provided in Table 9, based on the numerical results in Tables 7 and 8, which were obtained from the analyses. Relationship between generation number and fitness value is also presented in Fig. 6. Divergent behaviors of the curves primarily depend on the characteristics of randomly generated initial populations. According to the calculated fitness values, optimum configurations throughout three implant patterns are S4A and S3A designs, while S2B could also be suggested in case the application of a binary screw design is required. Having determined the optimum three configurations, critical von Mises stresses obtained from the analyses for S2B, S3A and S4A are presented in Figs. 7, 8 and 9, respectively.

When the results obtained from this study are examined within the scope of previous studies, there are various research representing similarity from different aspects to the optimum configuration of screws. Maurer et al. [50] performed mechanical tests on human cadaver bones and stated that the use of twin screws is an acceptable method in the treatment of femoral neck fractures. Xarchas et al. [51] emphasized that implants made using binary cannulated screws are a less damaging method for bone and soft tissues and argued that the binary screws applied in the correct position may be sufficient for the treatment of femoral neck fractures. Walker et al. [52] also showed that the use of multiple screws is very important for stability in femoral neck fractures and emphasized that the use of binary screws is sufficient for stabilization in the femoral neck fracture. On the other hand, Wu [53] stated that the application of the inverted triangle screw gives quite good results in femoral neck fractures. Similarly, Ly and Swiontkowski [54], Gurusamy et al. [55], and Yang et al. [56] recommended

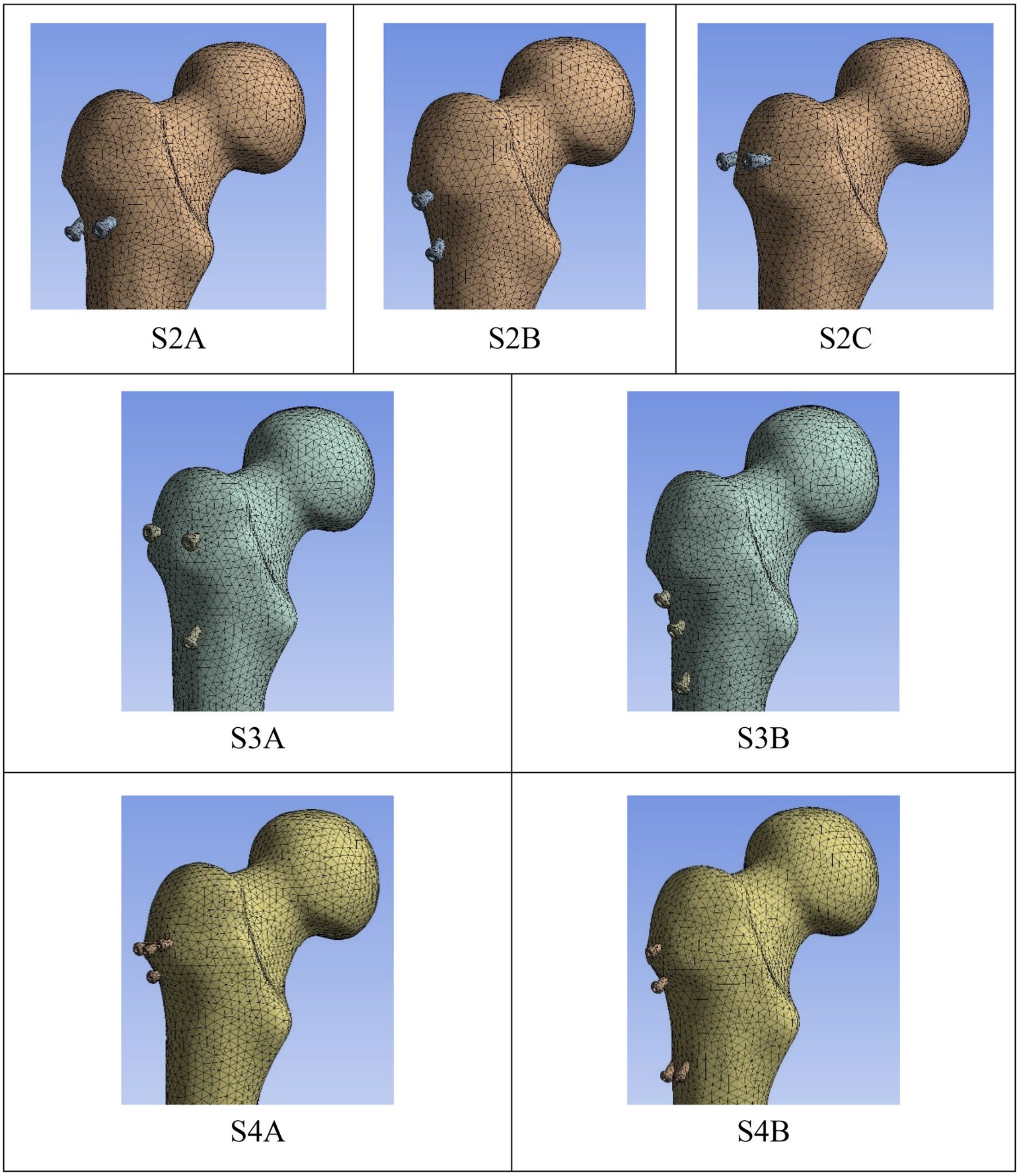

Fig. 5 Mesh details of the implant models

the use of inverted three screws in the treatment of femoral neck fractures. Apart from these studies, Satish et al. [57] emphasized that the four screws fixation gives good stability, allows controlled collapse, avoids fixation failure and achieves predictable bone healing in displaced femoral neck fracture in patients ≥ 50 years of age. Gümüştaş et al. [58] also conducted some biomechanical tests on femur bone and reported that four cannulated screws fixation may provide a beneficial contribution to fixation stability in the treatment of unstable femoral neck fractures. Rajnish et al. [59] also reported that the use of four screws for fixation of intracapsular neck of femur fracture contributed significantly to stabilization in femoral neck fractures. The arrangement of the screws proposed in the study is in line from particular aspects with the results of previous studies. When the suggestions of these studies evaluated, it is clear that there is no absolute consensus for the optimal screw configuration in the treatment of femoral neck fractures. Despite there is not an identical optimum implant design study based on a computational optimization method in the literature, it could

Table 6 Total number of nodes and elements for the optimized designs

Optimum design	Nodes	Elements
S2A	66,770	43,026
S2B	65,729	42,335
S2C	64,569	41,548
S3A	75,447	48,385
S3B	78,213	50,304
S4A	85,904	55,218
S4B	87,939	56,502

be propounded that suggested designs of these study are not opposite to the general assumptions in terms of cannulated screw fixation approaches.

6 Conclusions and Future Research

The assessment and treatment of femoral neck fractures (FNFs) still remain a significant challenge in terms of the orthopedist perspective, despite the fact that it has been an important subject in recent years. To treat these fractures, internal fixation implants (IFIs) have been mostly used for the young patients. Today, there are several types of IFI patterns used in the FNFs to provide the orthopedic requirements. In this study, it is aimed to determine the optimum position, size and number of cannulated screws used in the treatment of FNFs by using genetic algorithm (GA) and finite element method (FEM). The study focuses on three types of cannulated screw fixation (CSFs); binary screw (S2), triple screw (S3) and quadruple screw (S4) patterns. The study is carried out on two main steps: determination of the implant design via GA and validation of the implant design via FEM. In the determination of the implant design via GA, all possibilities for the implementation of S2, S3 and S4 patterns are taken into consideration. Using predefined ranges for the design variables; initial population size values are 100, 200 and 400, while 232, 248 and 264 possible designs are applicable for S2, S3 and S4 patterns,

Table 7 Numerical results of the femur

	S2A	S2B	S2C	S3A	S3B	S4A	S4B
Total deformation (mm)	14.38	14.45	14.46	14.47	14.26	14.42	14.24
Von Mises stress (MPa)	23.68	22.29	25.65	23.69	30.41	23.65	32.12
Maximum principal stress (MPa)	42.87	34.73	37.12	39.84	40.11	42.48	41.72
Minimum principal stress (MPa)	35.78	35.84	50.33	35.82	35.33	36.05	36.06
Maximum shear stress (MPa)	2.74	2.71	2.88	3.19	3.41	4.60	5.04

Table 8 Numerical results of the screws

	S2A	S2B	S2C	S3A	S3B	S4A	S4B
Total deformation (mm)	13.84	13.89	13.44	14.25	13.92	13.84	13.65
Von Mises stress (MPa)	196.00	209.78	211.03	208.99	237.52	226.31	220.18
Maximum principal stress (MPa)	191.41	210.83	211.36	209.11	238.98	227.58	220.91
Minimum principal stress (MPa)	196.83	168.40	189.97	199.54	198.08	177.84	179.52
Maximum shear stress (MPa)	33.91	12.56	27.94	13.67	16.55	10.59	13.65

Table 9 Fitness values of the acquired optimum designs

	S2A	S2B	S2C	S3A	S3B	S4A	S4B
Fitness values	2.870	2.932	2.709	3.110	2.704	3.310	2.908

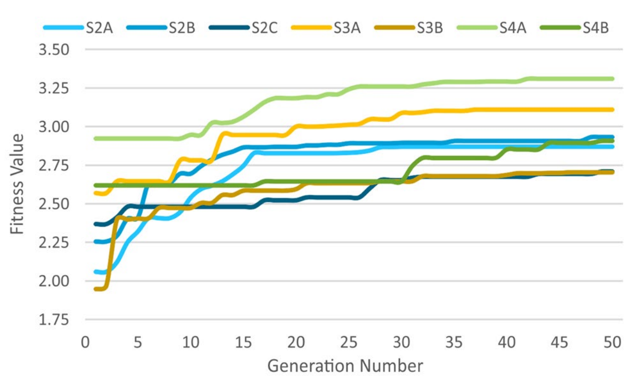

Fig. 6 Relationship between generation number and fitness value

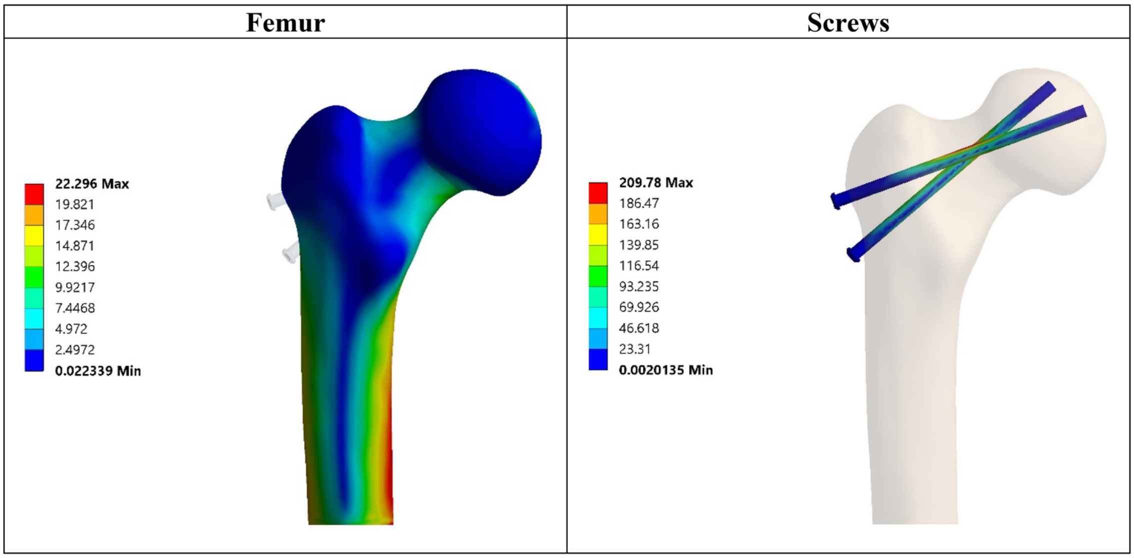

Fig. 7 Critical stress distributions on the femur and screws for S2B

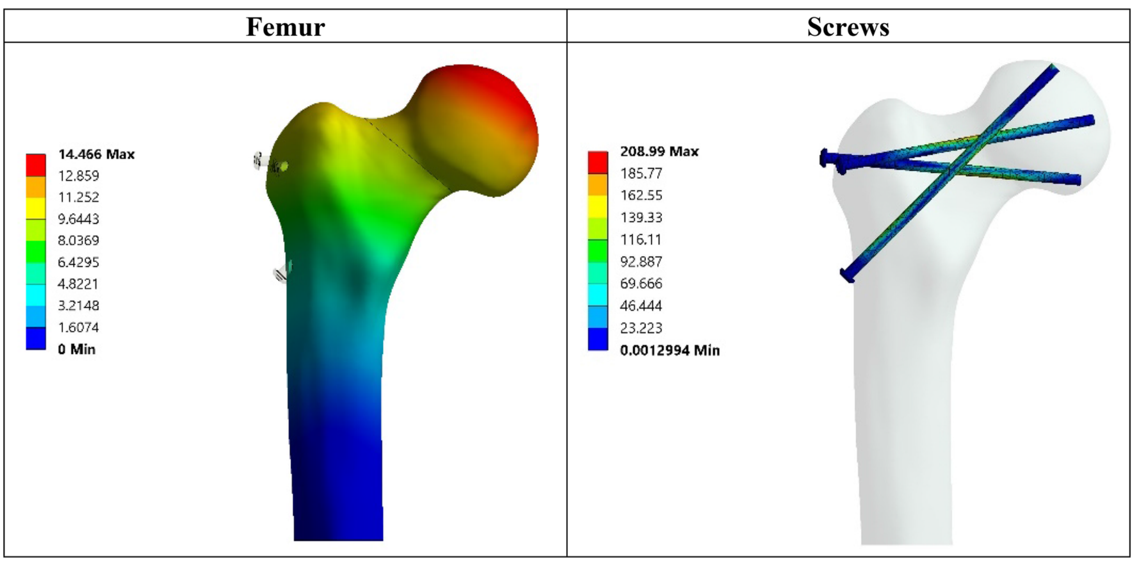

Fig. 8 Critical stress distributions on the femur and screws for S3A

respectively. Following this preliminary stage, GA is started and optimum implant schema is sought over iterative generations. Throughout the examination of the yielded results from each of the GA processes; implant designs, which are evaluated to be more advisable in terms of the applicability, are selected within the study. The selected designs are three configurations in S2, two configurations in S3 and two configurations in S4 patterns. In the second part of the study, the selected configurations are validated by using FEM. With the FEM, the selected designs are subjected to the same load effects; subsequently, critical stresses and deformations in bones and screws are examined. As a result of all evaluations and analyses, the most effective designs are achieved for the S2, S3 and S4 patterns. S2B, S3A and S4A designs are determined as the most suitable designs for S2, S3 and S4 patterns, respectively.

In this study, all of the possible combinations and screw sizes have been evaluated to determine the optimum conditions for fracture stability. Optimization approach in this study has revealed interesting and also easily applicable implant designs that have higher performances. Especially it is significant that achieving the optimum design by a

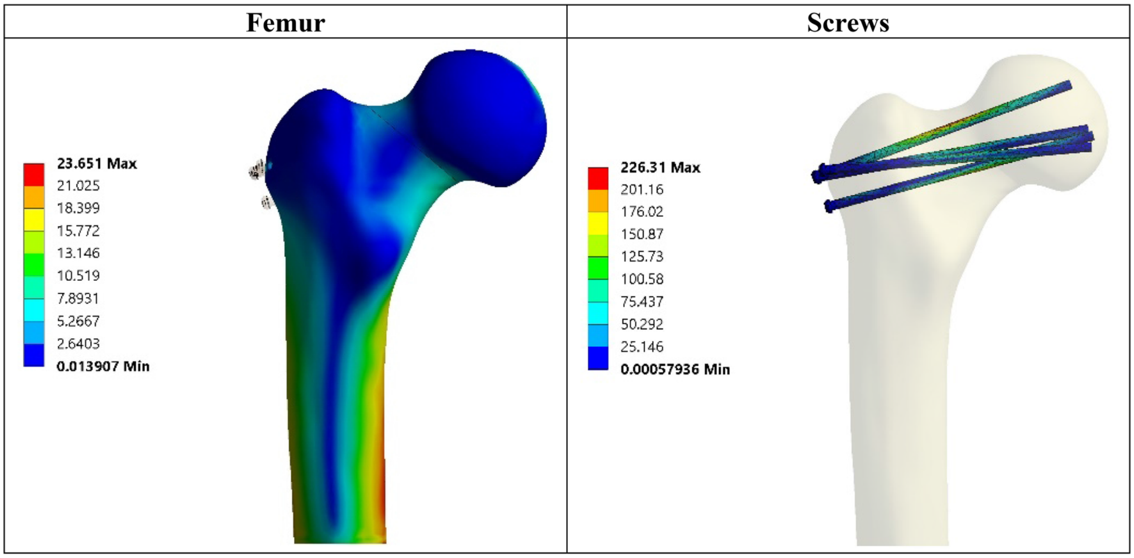

Fig. 9 Critical stress distributions on the femur and screws for S4A

limited number of analyses instead of a very high number of analyses puts the advantage of the GA. This study has the potential to be assumed as the validation of the mentioned approach, while future research considering the multi-load situations or different type of femoral neck fractures could present various implant designs.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Sandhu, H. S., Dhillon, M. S., & Jain, A. K. (2008). Femoral neck fractures. *Indian Journal of Orthopaedics, 42*(1), 1–2. https://doi.org/10.4103/0019-5413.38573.
2. Sensoz, E., Özkal, F. M., Acar, V., & Cakir, F. (2018). Finite element analysis of the impact of screw insertion distal to the trochanter minor on the risk of iatrogenic subtrochanteric fracture. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 232*(8), 807–818. https://doi.org/10.1177/0954411918789963.
3. Kemker, B., Magone, K., Owen, J., & Atkinson, P. (2017). Martin S & Atkinson TA sliding hip screw augmented with 2 screws is biomechanically similar to an inverted triad of cannulated screws in repair of a Pauwels type-III fracture. *Injury, 48*(8), 1743–1748. https://doi.org/10.1016/j.injury.2017.05.013.
4. Schaefer, T. K., Spross, C., Stoffel, K. K., & Yates, P. J. (2015). Biomechanical properties of a posterior fully threaded positioning screw for cannulated screw fixation of displaced neck of femur fractures. *Injury, 46*(11), 2130–2133. https://doi.org/10.1016/j.injury.2015.07.021.
5. Mei, J., Liu, S., Jia, G., Cui, X., Jiang, C., & Ou, Y. (2014). Finite element analysis of the effect of cannulated screw placement and drilling frequency on femoral neck fracture fixation. *Injury, 45*(12), 2045–2050. https://doi.org/10.1016/j.injury.2014.07.014.
6. Rooney, A., & Rollitt, N. (2013). Investigation into the outcomes following fixation of fractured neck of femurs with cannulated hip screws. *International Journal of Surgery, 11*(8), 663. https://doi.org/10.1016/j.ijsu.2013.06.409.
7. Holland, J. H. (1975). *Adaptation in natural and artificial systems*. Ann Arbor, MI: University of Michigan Press.
8. Goldberg, D. E. (1989). *Genetic algorithms in search, optimization and machine learning*. New York, NY: Addison-Wesley Publishing.
9. Walker, M., & Smith, R. E. (2003). A technique for the multiobjective optimisation of laminated composite structures using genetic algorithms and finite element analysis. *Composite Structures, 62*(1), 123–128. https://doi.org/10.1016/S0263-8223(03)00098-9.
10. Singh, S., Agrawal, S., Tiwari, A., Al-Helal, I. M., & Avasthi, D. V. (2015). Modeling and parameter optimization of hybrid single channel photovoltaic thermal module using genetic algorithms. *Solar Energy, 113*, 78–87. https://doi.org/10.1016/j.solener.2014.12.031.
11. Aydın, Z. (2006). *Öngerilmeli beton kirişli köprü üstyapılarının genetik algoritma ile optimum tasarımı*. PhD Thesis, Karadeniz Technical University, Turkey.
12. Nehdi, M., & Nikopour, H. (2011). Genetic algorithm model for shear capacity of RC beams reinforced with externally bonded FRP. *Materials and Structures, 44*, 1249–1258. https://doi.org/10.1617/s11527-010-9697-2.
13. Croce, F. D., Tadei, R., & Volta, G. (1995). A genetic algorithm for the job shop problem. *Computers & Operations Research, 22*(1), 20–30. https://doi.org/10.1016/0305-0548(93)E0015-L.
14. Deliktaş, B., Bikçe, M., Coşkun, H., & Türker, H. T. (2009). Betonarme kirişlerin optimum tasarımında genetik algoritma parametrelerinin etkisinin belirlenmesi. *Fırat University Journal of Engineering Science, 21*(2), 125–132.

15. Shukla, A., Pandey, H. M., & Mehrotra, D. (2015). Comparative review of selection techniques in genetic algorithm. In *1st International conference on futuristic trend in computational analysis and knowledge management* (ABLAZE-2015) (pp. 515–519).
16. Melanie, M. (1998). *An introduction to genetic algorithms*. London: The MIT Press.
17. De Jong, K., & Spears, W. (1992). A formal analysis of the role of multi-point crossover. *Annals of Mathematics and Artificial Intelligence, 5*, 1–26.
18. Hassanat, A., Almohammadi, K., Alkafaween, E., Abunawas, E., Hammouri, A., & Prasath, V. B. S. (2019). Choosing mutation and crossover ratios for genetic algorithms—A review with a new dynamic approach. *Information, 10*, 390. https://doi.org/10.3390/info10120390.
19. Saruhan, H. (2004). Genetic algorithms: An optimization technique. *Teknoloji, 7*(1), 105–114.
20. Gürünlü Alma, Ö. (2009). *Genetic algorithm based outlier detection using information criterion*. PhD thesis, Dokuz Eylül University, İzmir, Turkey.
21. Eiben, E., Michalewicz, Z., Schoenauer, M., & Smith, J. E. (2007). Parameter control in evolutionary algorithms. In *Parameter setting in evolutionary algorithms* (pp. 19–46). Berlin: Springer.
22. Hong, T. P., & Hong-Shung, W. (1996). A dynamic mutation genetic algorithm. *IEEE International Conference on Systems, Man and Cybernetics, 3*, 2000–2005.
23. Sarmady, S. (2007). An investigation on genetic algorithm parameters. Technical Report, School of Computer Science (p. 126). Universiti Sains Malaysia, Penang, Malaysia.
24. Goldberg, D. E. (1985). Optimal initial population size for binary coded genetic algorithms. TCGA Report 85001, The Clearinghouse for Genetic Algorithms, University of Alabama, Tuscaloosa, USA.
25. Hesser, J., Männer, R., & Stucky, O. (1991). On Steiner trees and genetic algorithms. In *Parallelism, learning, evolution* (pp. 509–525). Berlin: Springer.
26. East, I. R., & Rowe, J. (1996). Effects of isolation in a distributed population genetic algorithm. In *International conference on evolutionary computation–the 4th international conference on parallel problem solving from nature—PPSN IV* (pp. 408–419). Berlin: Springer.
27. Schep, N. W. L., Heintjes, R. J., Martens, E. P., van Dortmont, L. M. C., & van Vugt, A. B. (2004). Retrospective analysis of factors influencing the operative result after percutaneous osteosynthesis of intracapsular femoral neck fractures. *Injury, 35*(10), 1003–1009. https://doi.org/10.1016/j.injury.2003.07.001.
28. Lindequist, S. (1993). Cortical screw support in femoral neck fractures. A radiographic analysis of 87 fractures with a new mensuration technique. *Acta Orthopaedica Scandinavica, 64*(3), 289–293. https://doi.org/10.3109/17453679308993627.
29. Özkal, F. M., & Uysal, H. (2010). A new performance index formulation aiming to attain fully stressed designs for topology optimization problems. *Scientific Research and Essays, 5*(15), 2027–2036.
30. Özkal, F. M., Cakir, F., & Arkun, A. K. (2016). Finite element method for optimum design selection of carport structures under multiple load cases. *Advances in Production Engineering & Management, 11*(4), 287–298. https://doi.org/10.14743/apem2016.4.227.
31. Özkal, F. M., & Uysal, H. (2012). A fully stressed design method to determine the optimum strut-and-tie model for beam-column connections. *International Journal of Computational Methods, 9*(3), 1250035. https://doi.org/10.1142/S0219876212500351.
32. Günel U. Biomechanics of the hip joint. Editor Ege R: Hip Surgery and Problems. Ankara, Turkey: THK Printing House 1st edition (Turkish), 1994; 53–61.
33. Bayraktar HH, Morgan EF, Niebur GL Morris GE, Wong EK & Keaveny TM. Comparison of the elastic and yield properties of human femoral trabecular and cortical bone tissue. Journal of Biomechanics 2004; 37(1): 27–35.
34. Wang, J. (2005). Finite element analysis in the study of biomechanics of fracture. *Journal of Clinical Orthopaedics and Trauma, 8*, 283–285.
35. Bessho, M., Ohnishi, I., Matsuyama, J., Matsumoto, T., Imai, K., & Nakamura, K. (2007). Prediction of strength and strain of the proximal femur by a CT-based finite element method. *Journal of Biomechanics, 40*(8), 1745–1753. https://doi.org/10.1016/j.jbiomech.2006.08.003.
36. Varga, P., Baumbach, S., Pahr, D. H., Charlebois, M., & Zysset, P. K. (2009). Validation of an anatomy-specific finite element model of Colle's fracture. *Journal of Biomechanics, 42*(11), 1726–1731. https://doi.org/10.1016/j.jbiomech.2009.04.017.
37. Varga, P., Pahr, D. H., Baumbach, S., & Zysset, P. K. (2010). HR-pQCT based FE analysis of the most distal radius section provides an improved prediction of Colles' fracture load in vitro. *Bone, 47*(5), 982–988. https://doi.org/10.1016/j.bone.2010.08.002.
38. Hoffler, C. E., Moore, K. E., Kozloff, K., Zysset, P. K., Brown, M. B., & Goldstein, S. A. (2000). Heterogeneity of bone lamellar-level elastic moduli. *Bone, 26*(6), 603–609.
39. Zysset, P. K., Dallara, E., Varga, P., & Pahr, D. H. (2013). Finite element analysis for prediction of bone strength. *BoneKEy Reports, 2*, 386. https://doi.org/10.1038/bonekey.2013.120.
40. Xu, M., Yang, J., Lieberman, I. H., & Haddas, R. (2019). Finite element method-based study of pedicle screw-bone connection in pullout test and physiological spinal loads. *Medical Engineering & Physics, 67*, 11–21. https://doi.org/10.1016/j.medengphy.2019.03.004.
41. Kruszewski A, Piekarczyk P, Kwiatkowski K & Piszczatowski S. biomechanical evaluation of the stabilization used in the treatment of distal humerus intra-articular fractures. First European Biomedical Engineering Conference for Young Investigators, ENCY2015, Budapest, May 28–30, 2015.
42. Ambati, D. V., Wright, E. K., Jr., Lehman, R. A., Jr., Kang, D. G., Wagner, S. C., & Dmitriev, A. E. (2015). Bilateral pedicle screw fixation provides superior biomechanical stability in transforaminal lumbar interbody fusion: a finite element study. *The Spine Journal, 15*(8), 1812–1822. https://doi.org/10.1016/j.spinee.2014.06.015.
43. Ayturk, U. M., & Puttlitz, C. M. (2011). Parametric convergence sensitivity and validation of a finite element model of the human lumbar spine. *Computer Methods in Biomechanics and Biomedical Engineering, 14*(8), 695–705. https://doi.org/10.1080/10255842.2010.493517.
44. Rohlmann, A., Boustani, H. N., Bergmann, G., & Zander, T. (2010). Effect of a pedicle-screw-based motion preservation system on lumbar spine biomechanics: a probabilistic finite element study with subsequent sensitivity analysis. *Journal of Biomechanics, 43*(15), 2963–2969. https://doi.org/10.1016/j.jbiomech.2010.07.018.
45. Rohlmann, A., Burra, N. K., Zander, T., & Bergmann, G. (2007). Comparison of the effects of bilateral posterior dynamic and rigid fixation devices on the loads in the lumbar spine: a finite element analysis. *European Spine Journal, 16*(8), 1223–1231. https://doi.org/10.1007/s00586-006-0292-8.
46. Chen, S. I., Lin, R. M., & Chang, C. H. (2003). Biomechanical investigation of pedicle screw-vertebrae complex: a finite element approach using bonded and contact interface conditions. *Medical Engineering & Physics, 25*(4), 275–282. https://doi.org/10.1016/s1350-4533(02)00219-9.
47. Lenz, M., Gueorguiev, B., Joseph, S., Van Pol Der, B., Richards, R. G., Windolf, M., et al. (2012). Angulated locking plate in periprosthetic proximal femur fractures: biomechanical

testing of a new prototype plate. *Archives of Orthopaedic and Trauma Surgery, 132*, 1437–1444. https://doi.org/10.1007/s00402-012-1556-x.

48. Shah, S., Kim, S. Y. R., Dubov, A., Schemitsch, E. H., Bougherara, H., & Zdero, R. (2011). The biomechanics of plate fixation of periprosthetic femoral fractures near the tip of a total hip implant: cables, screws, or both? *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 225*, 845–856. https://doi.org/10.1177/0954411911413060.
49. Dubov, A., Kim, S. Y. R., Shah, S., Schemitsch, E. H., Zdero, R., & Bougherara, H. (2011). The biomechanics of plate repair of periprosthetic femur fractures near the tip of a total hip implant: the effect of cable-screw position. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 225*, 857–865. https://doi.org/10.1177/0954411911410642.
50. Maurer, S. G., Wright, K. E., Kummer, F. J., Zuckerman, J. D., & Koval, K. J. (2003). Two or three screws for fixation of femoral neck fractures? *American Journal of Orthopedics (Belle Mead NJ), 32*(9), 438–442.
51. Xarchas, K. C., Staikos, C. D., Pelekas, S., Vogiatzaki, T., Kazakos, K. J., & Verettas, D. A. (2007). Are two screws enough for fixation of femoral neck fractures? A Case series and review of the literature. *The Open Orthopaedics Journal, 1*, 4–8. https://doi.org/10.2174/1874325000701010004.
52. Walker, E., Mukherjee, D. P., Ogden, A. L., Sadasivan, K. K., & Albright, J. A. (2007). A biomechanical study of simulated femoral neck fracture fixation by cannulated screws: Effects of placement angle and number of screws. *American Journal of Orthopedics (Belle Mead NJ), 36*, 680–684.
53. Wu, C. C. (2010). Using biomechanics to improve the surgical technique for internal fixation of intracapsular femoral neck fractures. *Chang Gung Medical Journal, 33*(3), 241–251.
54. Ly TV & Swiontkowski MF. Treatment of femoral neck fractures in young adults. In: Azar FM, ed. Instructional Course Lectures. Vol. 58. IL, U.S.A.: American Academy of Orthopedic Surgeons, 2009; 69–81.
55. Gurusamy, K., Parker, M. J., & Rowlands, T. K. (2005). The complications of displaced intracapsular fractures of the hip: The effect of screw positioning and angulation on fracture healing. *The Bone & Joint Journal, 87*(5), 632–634. https://doi.org/10.1302/0301-620X.87B5.15237.
56. Yang, J. J., Lin, L. C., Chao, K. H., Chuang, S. Y., Wu, C. C., Yeh, T. T., et al. (2013). Risk factors for nonunion in patients with intracapsular femoral neck fractures treated with three cannulated screws placed in either a triangle or an inverted triangle configuration. *The Journal of Bone and Joint Surgery, 95*(1), 61–69. https://doi.org/10.2106/JBJS.K.01081.
57. Satish, B. R., Ranganadham, A. V., Ramalingam, K., & Tripathy, S. K. (2013). Four quadrant parallel peripheral screw fixation for displaced femoral neck fractures in elderly patients. *Indian Journal of Orthopaedics, 47*(2), 174–181. https://doi.org/10.4103/0019-5413.108912.
58. Gümüstas, S. A., Tosun, H. B., Air, I., Orak, M. M., Onay, T., & Okçu, G. (2014). Influence of number and orientation of screws on stability in the internal fixation of unstable femoral neck fractures. *Acta Orthopaedica et Traumatologica Turcica, 48*(6), 673–678. https://doi.org/10.3944/AOTT.2014.14.0088.
59. Rajnish, R. K., Haq, R. U., Aggarwal, A. N., Verma, N., Pandey, R., & Bhayana, H. (2019). Four screws diamond configuration fixation for displaced, comminuted intracapsular fracture neck femur in young adults. *Indian Journal of Orthopaedics, 53*(1), 70–76. https://doi.org/10.4103/ortho.IJOrtho_333_17.