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Original Article

Biomechanical Analysis of Window Configuration of Femur under Different Loading Conditions

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Abstract

Background: In surgeries, when making a window in the bone cortex is necessary, a circular window is usually recommended. A review of the literature did not yield any positive evidence indicating the preference for the circular shape under bending and compression loading.
Objectives: In this study, we examined this issue using two methods, including software analysis and performing load tests in laboratory.
Methods: Windows of different shapes with the same area were made in 40 femoral bones of the same-weight New Zealand rabbits, and then they were put under bending and compression force by a hydraulic device in the laboratory to measure the force required to fracture the bone by a computer. Simultaneously, ANSYS® software was used to simulate the test by the Biomechanics Research Team of the University of Technology.
Results: According to the results obtained from software analysis and simulation, under compression and bending loading conditions, the mean fracture force in a trapezoidal shape was more than that in circular, square, and triangular shapes. These results were also confirmed in the experiments.
Conclusion: Based on the results, no significant difference was observed between these shapes under the bending force. Moreover, under compression loading, no significant difference was found between trapezoidal and circular shapes.

Keywords: Rabbit femur, Compression, Bending.

Introduction

In most orthopedic surgeries performed for the diagnosis and treatment of diseases, such as infections, tumors, and inflammation, a window is required in the cortex of long bones. These windows provide a way for biopsy, drainage, and curettage of the bone lesions.[1-4] In each of these cases, especially in the long bones of the lower extremities that bear the body weight, a cortical defect with any size potentially increases the risk of fracture.[5-8] These fractures, particularly at the diaphyseal level, impose the risk of other surgeries for the reduction and fixation of the fractures. In biopsies, this phenomenon aggravates the infection and contaminates other tissues with neoplastic lesions and can also lead to amputation.[1] By examining the circular defects, Bechtol believes that the effects of stress accumulation around any hole with a diameter of less than 30% of the diameter of the bone are not different from one another. This issue was also confirmed by Edgerton.[9-11] By analyzing the data, Hipp reported that there was no linear relationship between the hole size and the reduction in bone strength.[12] By studying the pig femur compared to its simulated structure through the finite element method, MacBroom et al., found that a hole with a diameter of 20% reduces bone strength by 40%.[13] Brent et al., also conducted a study on human fibular diaphysis and reported that even one hole with a diameter of 3.5 mm can reduce bone strength by 40% under bending force.[14] Clark et al., showed that if the window in long bones is longitudinal, the width of the window is more important than its length in terms of reducing bone strength.[15] Moreover, Elias et al., confirmed this issue through computer simulations and observed that the highest accumulation of stress occurs around the corners of both sides of the window if the window is longitudinal.[16] Specifications of the force involved in fracture are the amount, direction, and duration of the force exerted to the bone. The forces can be exerted through bending, compression and torsion. If a hole is created in the cortex, the main factor causing resistance to these forces weakens and the risk of fracture increases.[17-20]

Regarding the pig femur, Kevin et al., created a 4.5 mm hole in both sides of the diaphyseal cortex (10% of the diameter) and placed the bone under torsion loading and indicated that the fracture line passed through the hole due to the weakness of the bone in that area. They also reported that filling the hole with objects like screws or elastic modulus similar to bone like a pop can compensate for the reduced strength to a large extent.[22]

Generally, a circular window is recommended in surgeries that require creating a window in the bone cortex for any reason.[9,21,31] According to Camargo et al., study that was conducted on the dog femur under bending loading, no significant difference was observed between the reduced bone strength caused by the circular window in the diaphyseal cortex and the square window, the diameter of which was parallel to the axis of the bone.[23] Literature review shows no study to date has examined the comparison of the circular holes in the cortex and non-circular holes under compression and bending loading conditions. This study aimed to examine the effect of window configuration of the bone cortex on its strength. This study was performed in two separate procedures, including laboratory tests and computer simulations through the finite element method. In industry, the finite element method is widely used for examining the strength of structures and materials with regard to different properties and states of the constituent elements of the structure. Since it is possible to simulate bone properties (elasticity and plasticity), this method is currently used for examining the bone strength and predicting its effective factors.[16]

Objectives

In current study, we examined this issue using two methods, including software analysis and performing load tests in laboratory.

Materials and Methods

This experimental study was carried up from June 2018 to May 2019 at Baqiyatallah University of medical sciences, Tehran, Iran. A total of 40 New Zealand male rabbits (two years old and two kilograms) were euthanatized in this study. By disarticulating hips and knees in these rabbits, 40 femurs were obtained. Soft tissues were separated from the femur bones. Then, 20 samples were randomly divided into four groups and numbered based table randomization. Biometric characteristics of bones, including length, weight, and diameter of the diaphysis were measured using instruments such as a caliper and digital scale. The samples were then placed in plastic bags and then kept at -20 °C. In order to create a defect, the samples were first placed at room temperature for four hours. Then, in each group of the samples, a window was created in one of the configurations of a square, circle, triangle, and trapezoid with the same area in the anterior cortex of the midshaft, in the middle of the diaphysis through a microbur. Afterward, these shapes were created quite similar through a metal stencil and CNC machine with precise dimensions. All shapes were made in all bones in the same direction to the central axis of the bone. Then, the samples were again frozen and kept at -20 °C. In order to perform the load tests, the samples were again placed at room temperature. Next, each group of the samples was divided into two groups of five samples and each of these groups was separately influenced by compression and bending force through Santam hydraulic device. The applied force continued until the diaphysis was fractured. Finally, the force applied to break the bone was measured by a computer.

All cases were maintained under conventional laboratory conditions and presented with identical food and water during the research time. After recovery, the cases were separately housed in separate cages. The cages were cleaned daily and kept free from infectious causes. This study was approved by the Animal Medical Ethics Committee of Baqiyatallah University of Medical Sciences. At the same time, our colleagues in the research team of the Amirkabir University of Technology used CT scans at a distance of 5 mm to simulate femur bone through the ANSYS software and finite element method, and designed windows in the middle of diaphysis similar to the laboratory samples. Then, the models were virtually loaded and their behaviors were analyzed by the ANSYS software (Version 18).

The data analysis was conducted using SPSS 21.0. The Kruskal-Wallis and Mann Whitney u was performed to analyze the differences among the 4 and 2 groups. P-values of less than 0.05 were regarded as statistically significant.

Results

Software Analysis

Table-1 represents the results of the computer simulation.

Table 1. Results of computer simulation

	Compression	3PBending
Square	1042N	**471N**
Circle	1595N	**455N**
Triangle	1438N	**366N**
Trapezoid	2130N	**609N**

The computer also displayed stress accumulation points. For example, the effect of the circular window on stress distribution under bending loading is shown in Figure 1.

Based on the results, a greater force is required for breaking a bone with a trapezoidal window compared to the bones with circular, square, and triangular shapes under compression and bending loading. The triangular shape indicated the lowest strength under all types of loading. In the case of circular and square windows, the bone strength depended on the type of loading. Under bending loading, the strength of the bone with a square window was preserved more and under compression loading, a greater force was needed to break the bone with a circular window.

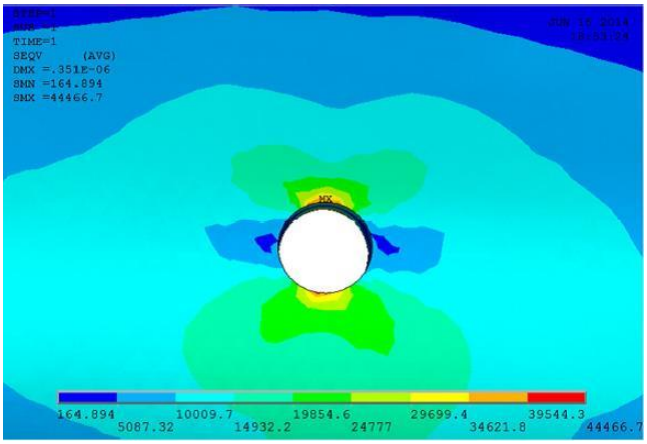

Figure 1. Effects of circular holes on stress distribution under flexural load

Laboratory Test Results

The biometric characteristics of the samples under bending and compression loading conditions are presented in Table 2. The results revealed that there was no significant difference between the samples in term of biometrics (P>0.05).

Table 3 presents the results of the maximum fracture force under bending and compression loading conditions.

Based on results, the mean fracture force under both types of loading in the bone with a trapezoidal hole was more than other shapes (P<0.001). The mean force required to fracture bones with square windows was greater under bending loading (P<0.001). The mean force required to fracture bones with circular windows was higher under compression loading (P<0.001). Bones with triangular windows indicated a greater reduction in strength under all types of loading. Under bending loading, there was no significant difference in the mean fracture force between bones with different window shapes (P>0.05). Moreover, under compression loading, there was no significant difference in the mean fracture force between bones with trapezoidal windows and samples with circular windows (P>0.05). Also, under this type of loading, no significant difference was observed in the mean fracture force between samples with square windows and triangular windows (P>0.05). But, a significant difference was observed in the fracture force between bones with circular and square windows, as well as between bones with circular and triangular windows (P<0.001).

Table 2. Profile biometric samples in both bending and pressure loading

			N	Mean	SD	P-value
Bending	weight	Square	5	8.6	0.59	0.56
		Circle	5	8.56	0.50	
		Triangle	5	8.22	0.58	
		Trapezium	5	8.6	0.44	
		Total	20	8.495	0.51	
	length	Square	5	8.94	0.11	
		Circle	5	8.76	0.24	
		Triangle	5	8.68	0.24	
		Trapezium	5	8.76	0.24	
		Total	20	8.785	0.22	
	diameter	Square	5	8.02	0.14	
		Circle	5	7.94	0.15	
		Triangle	5	8.04	0.11	
		Trapezium	5	7.96	0.11	
		Total	20	7.99	0.12	
			N	Mean	SD	P-value

Compression	weight	Square	5	8.56	0.49	0.65
		Circle	5	8.44	0.51	
		Triangle	5	8.6	0.54	
		Trapezium	5	8.34	0.55	
		Total	20	8.485	0.49	
	length	Square	5	8.94	0.15	
		Circle	5	9	0.10	
		Triangle	5	8.84	0.15	
		Trapezium	5	8.64	0.25	
		Total	20	8.855	0.21	
	diameter	Square	5	8.1	0.10	
		Circle	5	8	0.07	
		Triangle	5	8.02	0.08	
		Trapezium	5	8.02	0.10	
		Total	20	8.035	0.09	

Table 3. Descriptive data based on cavity shape, average failure bending and pressure in each group form

Bending/Compression		**N**	**Mean**	**SD**	**P-value**
Bending	Square	5	1.0640E2	21.46625	0.65
	Circle	5	1.0020E2	26.94810	
	Triangle	5	87.8000	22.44326	
	Trapezium	5	1.1620E2	23.20991	
	Total	20	1.0265E2	24.10345	
Compression	Square	5	2.2420E2	35.53449	<0.001
	Circle	5	3.0880E2	65.88399	
	Triangle	5	1.9080E2	15.44992	
	Trapezium	5	3.5600E2	45.56314	
	Total	20	2.6995E2	78.81723	

Discussion

There was no significant difference in biometric characteristics among femur samples, which were obtained from rabbits of the same breed, age, and weight, and they were kept under the same conditions at -20 °C. A stencil was used to create defects in the same size and area. Despite the differences in the shapes of the defects; they were created in a point with a fixed distance from the bone axis. All of these conditions reduced the risk of errors in the tests. This study aimed to achieve comparable parameters allowing us to examine the effect of window configuration of the bone cortex on its strength. Until now, to the best of our knowledge, no similar study was found on the effect of window configuration of the bone cortex on its strength under bending and compression loading conditions.

In this study, we examined the ability of bones with circular defects in the cortex that are typically used in biopsies and square, triangular, and trapezoidal defects to resist fracture under bending and compression loading conditions. The present study was conducted using software analysis by Amir Kabir University of Technology, and laboratory tests. The bones with trapezoidal defects of the cortex indicated more strength in both methods. However, this feature was only significant in comparison with some shapes and under same loading conditions. In general, no significant difference was observed in the fracture force between bones with trapezoidal defects and circular defects.

The results indicated that under bending loading, no specific window configuration had a preference for maintaining bone strength. Under compression loading, no significant difference was found between bones with trapezoidal and circular defects, as well as between bones with square and triangular defects. The effect of a specific window configuration on the bone strength was not constant under various conditions. This result was consistent with the findings of other previous studies.[15,23] Therefore, the presence of a hole or window in the bone cortex reduces its strength against forces and stresses. The fracture line always passes through the window.[10,22]

Stress concentration or stress accumulation in relation to the shape of the window is a known phenomenon, which its effect can be easily observed in isotropic and elastic materials. However, the bone has a more complex structure.[24,25] The bone does not have a homogenous structure. The trabecular structure of bones with its special arrangements and constituent materials provides the isotropic and elastic properties. The diaphyseal cortex consists of two components, including hydroxyapatite (a material with a high strength causing rigidity) and collagen (a protein with elastic and plastic properties).[26-28] Stress accumulation is more observed in shapes that their sides suddenly change direction, like triangles. As the angle is more acute, the stress accumulation is greater, and consequently the bone resistance to stress reduces more.[16,28] However, the round corners of the window are not the only factor affecting bone strength. Theoretical studies have calculated the value of K coefficients for each window configuration. For example, the fracture coefficient for an isosceles triangle with its altitude parallel to the bone axis is higher than that of other shapes, and the fracture coefficient for a square with a diameter parallel to the bone axis is less than a circle. The coefficient for an oval is between these two shapes.[29] The aspect ratio of a window is another factor affecting the strength. In this regard, Elias et al., also confirmed this issue through the finite element method.[15,16,30] The results can be explained similar in trapezoids with the same area, the width can be greater than the length, and such a characteristic is not seen in circles due to their round corners. Due to the superiority of the width to length ratio over the stress concentration in trapezoids, its strength was maintained more in comparison with the circular window. However, this difference was not significant. The stress concentration in circular windows compared with other shapes is a more effective factor in maintaining strength.

Using the finite element method, Edgerton et al., indicated that the strength greatly reduces in holes with about half of the diameter of the diaphysis. This result can justify the lack of significant difference in the fracture force between different shapes under bending loading.[11]

Conclusions

Due to the special structure of the bone, irregular edges of the windows and cutting the trabeculae can act as an effective factor for stress concentration and the corners can increase its effects. Therefore, this factor can interpret the inconsistency in results of theoretical studies and laboratory tests. Using an accurate metal stencil for each shape and an appropriate microbur for microsurgery instead of osteotome, drill and oscillator led to the creation of windows with more regular edges and the elimination of edge irregularities helped the laboratory conditions become closer to the theoretical conditions. Therefore, the theoretical results, simulation and laboratory results became more consistent.

In other words, a surgeon should try to remove factors involved in the stress accumulation, such as acute angles and sudden changes in the sides of the window. Round edges can reduce stress accumulation and prevent pathological fractures. However, in response to a window in the cortex, the bone has a dynamic resistance compatible with stressful conditions, including the age at the time of stress, anatomical location of stress, and characteristics of stress, such as the frequency and its intensity, which indicates different responses depending on each of the conditions.[22]

Therefore, bone conditions in living organisms are different from those of a corpse and thus, further studies are needed to generalize these results.

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Authors’ Contribution

All authors pass the four criteria for authorship contribution based on the International Committee of Medical Journal Editors (ICMJE) recommendations.

Conflict of Interests

The authors declared no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

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