BIOMECHANICAL ANALYSIS OF TWO-POINT ASYMMETRIC SCREW FIXATION WITH IMPLANT FOR FEMORAL NECK FRACTURE

Dmitrij B. KAREV*, **Vladimir G. BARSUKOV****

*The Grodno State Medical University, 230009 ul. Gorkogo 80, Grodno, Belarus,
**The Yanka Kupala State University of Grodno, 230023, ul. Orzeshko 22,Grodno, Belarus,

bkarev@gmail.com, v.g.barsukov@grsu.by

Abstract: Stressed state peculiarities of cortical and trabecular bones by two-point asymmetric screw fixation with implant for femoral neck fracture are studied. Layer construction mechanic methods are used for analysis of stresses in cortical and trabecular bones. Biomechanical conditions for non-opening of the junction of the bone parts being joined are determined. It has been found that the total tightness of the broken parts when they rest against each other is secured over the whole fracture section without junction opening under condition that fixing screws are positioned in the trabecular bone without penetration of the thread side surface into cortical bone.

Key words: Femoral Neck Fracture, Screw Fixation, Stressed State, Cortical Bone, Trabecular Bone

1. INTRODUCTION

The main task of screw fixation for femoral neck fracture is securing the tightness (compression) of broken parts when they rest against each other. This tightness can be secured by means of different connections: one-point (central and eccentric); two-point (symmetric or asymmetric); three-point (symmetric, asymmetric with two bearing and one auxiliary fastening elements); four-point, etc. Extensive review of the world scientific and technical achievements in this field is given in the research papers (Manniger et al., 2007; Mow and Huiskes, 2005; Booth et al., 1998). The analysis of the published works shows that the major disadvantage of one-point fixation is the difficulty in preventing the parts being joined from possible rotation. In addition, one-point fixation stipulates the centric fixing element position which deteriorates blood circulation and fosters avascular necrosis of femoral head in case of femoral neck stabilization. Two-point, three-point and other multiple-point fixation secures broken parts from mutual rotation but a big number of fixation points makes osteosynthesis operation more traumatic and labour-consuming. Therefore, two-point and three-point fixation is considered to be preferable (Fig.1).

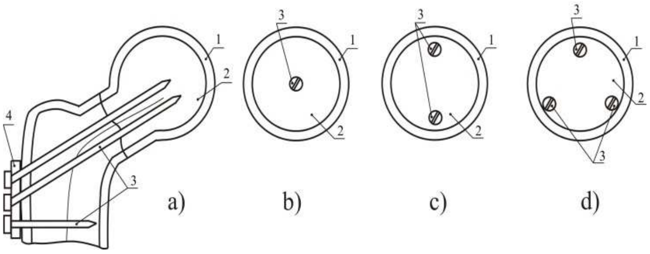

Fig. 1. Conventional screw fixation for femoral neck fractures: a – side view; b – one-point; c – two-point symmetric; d – three-point symmetric fixation: 1 – cortical bone; 2 – trabecular bone; 3 – fixing screw; 4 – plate

Moreover, the three-point fixation under certain conditions (strain-retention loss of one of the screws) may work as a two-point asymmetric fixation.

In spite of intensive research and development work, a number of issues of deflected mode of the broken femoral neck parts being joined by means of different types of fixation have been studied so far insufficiently. Approaches described in the literature (Booth et al.,1998; Akulich and Denisov, 2008; Yeremin, 2010) are based on simplified biomechanical models which consider bone tissue as homogeneous material. This introduces significant errors at determining the tension in the parts being joined.

On the other hand, modified fixation methods have been used increasingly in recent medical practice wherein one of the fixing screws is substituted with an implant of definite shape which is made from the bone of the person being operated upon (Karev, 2012) (Fig.2).

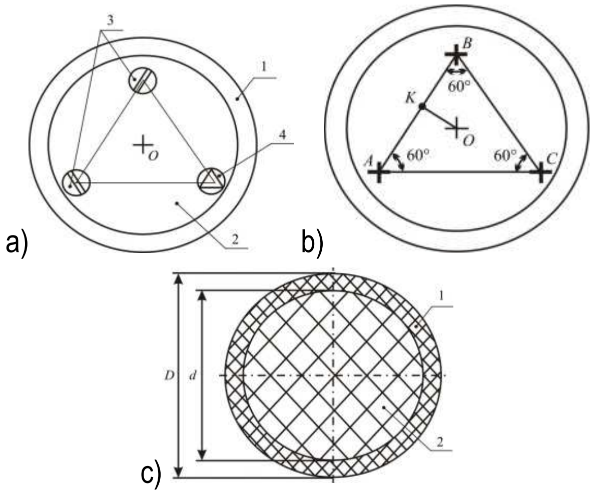

Fig. 2. Graphic representation of the basic scheme (a) and characteristic dimensional parameters (b), (c) for two-point asymmetric screw fixation with an implant: $OK = e$, $OB = OA = R$: 1 – cortical bone; 2 – trabecular bone; 3 – fixing screw; 4 – implant

These methods make it possible to decrease the proportion of foreign objects (fixing screws), facilitate drainage and thereby improve recovery of the femoral head in postoperative period by reducing the time of medical treatment. However, the biomechanical aspect of such approach is still not fully investigated which makes it difficult to analyze the potentialities of this osteosynthesis method.

The objective of this work is development of improved calculation methods based on taking into account differences of deformation-stress properties of the outer and inner layers of the bone and the performance of bones tension analysis in transfer from three-point to two-point asymmetric fixation type with an implant.

2. BIOMECHANICAL ANALYSIS OF FIXATION TYPES

From the mechanics of materials perspective, the femoral neck represents a two-layer material consisting of solid outer cortical layer 1 of diameter *D* and relatively less solid inner trabecular layer 2 of diameter *d* (Fig. 2c). Specifically, according to the data from literary sources the breaking stress of cortical bone under longitudinal tension is 133 MPa (Mow and Huiskes, 2005), under longitudinal compression – 193 MPa; the breaking stress of trabecular bone is from 3.65 to 9.1 MPa (Yeremin, 2010); modulus of elongation: 17–25 GPa for cortical bone and 0.2–2.5 GPa for trabecular bone (Mow and Huiskes, 2005). Indicator values of mechanical properties depend on age-related and pathological changes of bone tissue as a consequence of past medical history as well as on the loading speed while testing (Mow and Huiskes, 2005).

Significant (by order of magnitude greater) difference in physical and mechanical properties of bone tissue of cortical and trabecular layers results in nonuniform distribution of compression stress in bone section when fixing screws are tightened. Even if the screws are tightened uniformly in case of three-point symmetric fixation (Fig.1c), the tension, being uniform within each layer, differs at the layer borders proportionally to the differences in elasticity modulus (Fig. 3).

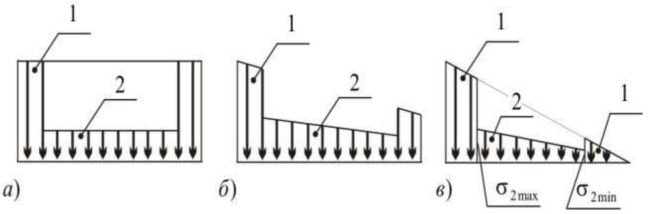

Fig. 3. Tension distribution pattern from the screw tightening over the section: a) – uniform tightening; b) – nonuniform tightening; c) – threshold case (junction opening); 1 – cortical bone; 2 – trabecular bone

In case of strain-retention loss of one of the screws, section tension distribution within each layer becomes nonuniform (Fig. 3b). At that, nonuniformity grows proportionally to the strain-retention loss degree. Maximum permissible is the case when the pressure (compression) in the outer layer becomes equal to zero (Fig. 3c). Further release of the screw strain is inadmissible as it is followed by the junction opening of the bone parts being joined.

It should be noted that the same compression distribution relevant to our case can be achieved by implementation of two-point asymmetric fixation illustrated in Fig. 2a. Let us analyze this type of fixation. Under the condition of uniform tightening of the fixing screws 1 and 2 with equal strain *V* their resultant (integral force) *F*=2*V* will be applied to the point *K*. Since from mechanical point of view this type of fixation corresponds to eccentrical compression of the layered structure by the applied effort which is positioned at the distance of eccentricity *e*=*OK* from the longitudinal axis, such loading can be considered as combination of centric compression with effort *F* and bending moment *M*=*F***e* (Vinokurov et al., 1998; Minenkov and Stasenko, 1977).

Corresponding formulas of mechanics of layered structures (Vinokurov et al., 1998; Minenkov and Stasenko, 1977), adapted to the calculation model under consideration are used for the evaluation of compression in each layer within femoral neck.

Specifically, for compression stresses in the cortical bone:

$$\sigma_{1c} = \frac{FE_1}{A_1E_1 + A_2E_2}, \tag{1}$$

and for the trabecular bone:

$$\sigma_{2c} = \frac{FE_2}{A_1E_1 + A_2E_2}, \tag{2}$$

where: σ_{1c} , σ_{2c} are correspondingly compression stress in cortical (1) and trabecular (2) layers of femoral neck; E_1 and E_2 – elasticity moduli of cortical and trabecular layers; A_1 and A_2 – cross-sectional area of cortical and trabecular layers; *F* – integral force of screw strain.

Bending stress for layered material (Vinokurov et al., 1998; Minenkov and Stasenko, 1977) in any point at the distance *r* from centroid of section:
in cortical bone:

$$\sigma_{1b} = \frac{M \cdot E_1 \cdot r}{E_1I_1 + E_2I_2} \tag{3}$$

and in trabecular bone:

$$\sigma_{2b} = \frac{M \cdot E_2 \cdot r}{E_1I_1 + E_2I_2} \tag{4}$$

Here σ_{1b} is the bending stress in the outer (cortical) layer; σ_{2b} is bending stress in the trabecular layer; I_1 and I_2 – correspondingly axial moment of inertia of cortical and trabecular layers of bone section.

Calculation values of areas of cortical A_1 and trabecular A_2 layers and corresponding axial moments of inertia of section I_1 and I_2 can be expressed in initial approximation through outer *D* and inner *d* diameters (fig.2c) by means of the following correspondences

$$A_1 = \frac{\pi D^2}{4}(1-\alpha^2) \tag{5}$$

$$A_2 = \frac{\pi D^2}{4}\alpha^2 \tag{6}$$

$$I_1 = \frac{\pi D^4}{64}\left(1-\alpha^4\right) \tag{7}$$

$$I_2 = \frac{\pi D^4}{64}\alpha^4 \tag{8}$$

where *α*=*d*/*D*.

The formulae given above (5)–(8) are approximate because they do not take into account the weakening of sections by the openings intended for fixing screws and the implant due to its little effect.

With regard to (5)–(8) formulae (1)–(4) for stresses calculation are brought to the following form:

Compression stress in a cortical bone:

$$\sigma_{1c} = \frac{4FE_1}{\pi D^2\left[\left(1-\alpha^2\right)E_1+\alpha^2E_2\right]} \tag{9}$$

compression stress in a trabecular bone:

$$\sigma_{2c} = \frac{4FE_2}{\pi D^2\left[\left(1-\alpha^2\right)E_1+\alpha^2E_2\right]} \tag{10}$$

bending stress in a cortical bone:

$$\sigma_{1b} = \frac{64\cdot M\cdot E_1\cdot r}{\pi D^4\left[\left(1-\alpha^4\right)E_1+\alpha^4E_2\right]} \tag{11}$$

bending stress in a trabecular bone:

$$\sigma_{2b} = \frac{64\cdot M\cdot E_2\cdot r}{\pi D^4\left[\left(1-\alpha^4\right)E_1+\alpha^4E_2\right]} \tag{12}$$

Maximum bending stress values are obtained if:

$$M = F * e_{max}, \tag{13}$$

where e_{max} – maximum eccentricity of integral force application F.

The maximum resulting stresses magnitude will be observed in the outermost point from centroid of section of the corresponding layer from the side where the compression stress and bending stress coincide, and the minimum ones – at the same kind of point from the side where the compression stress and bending stress signs are opposite.

3. BIOMECHANICAL CONDITION FOR NON-OPENING OF THE JUNCTION OF THE BONE PARTS BEING JOINED

The criterion for non-opening of the junction is the absence of tensile stress in the zone where the signs of compression and bending stress are opposite. Having equated the maximum bending stress to compression stress after transformation we get the value of maximum permissible level of eccentricity e_{max} of screw strain resultant application:

for cortical bone:

$$e_{1\max} = \frac{D\left(1-\alpha^4\right)E_1+\alpha^4E_2}{8\left[\left(1-\alpha^2\right)E_1+\alpha^2E_2\right]} \tag{14}$$

for trabecular bone:

$$e_{2\max} = \frac{D\left(1-\alpha^4\right)E_1+\alpha^4E_2}{8\alpha\left[\left(1-\alpha^2\right)E_1+\alpha^2E_2\right]} \tag{15}$$

Maximum permissible relative eccentricity value of screw strain resultant application:

for cortical bone:

$$\frac{e_{1\max}}{D} = \frac{1}{8}\frac{\left(1-\alpha^4\right)E_1+\alpha^4E_2}{\left[\left(1-\alpha^2\right)E_1+\alpha^2E_2\right]} \tag{16}$$

for trabecular bone:

$$\frac{e_{2\max}}{D} = \frac{1}{8}\frac{\left(1-\alpha^4\right)E_1+\alpha^4E_2}{\alpha\left[\left(1-\alpha^2\right)E_1+\alpha^2E_2\right]} \tag{17}$$

For illustrative purposes the tables (1, 2, 3) contain calculated magnitudes of the maximum permissible eccentricity value by condition of non-opening of the junction in cortical and trabecular bone layers. Calculations were made through the example of widely occurring diameter of femoral neck D=40 mm for different values of elasticity moduli of layer materials in case of two-point fixation with uniform screw strains.

Tab. 1. The calculated magnitudes of dimensional parameters for value of cortical bone elasticity modulus E_1=17 GPa

Name and identifier of dimensional parameter	Elasticity modulus of trabecular bone E_2, GPa					
	0.25	0.5	1.0	1.5	2.0	2.5
Maximal relative eccentricity for cortical bone e_{1max}/D	0.24	0.24	0.22	0.21	0.21	0.20
Maximal relative eccentricity for trabecular bone e_{2max}/D	0.27	0.26	0.25	0.24	0.23	0.22
Maximal value of eccentricity for cortical bone e_{1max}, mm	9.72	9.4	8.94	8.54	8.20	7.9
Maximal value of eccentricity for trabecular bone e_{2max}, mm	10.8	10.4	9.93	9.48	9.11	8.78

Tab. 2. The calculated magnitudes of dimensional parameters for value of cortical bone elasticity modulus E_1=20 GPa

Identifier of dimensional parameter	Elasticity modulus of trabecular bone E_2,GPa					
	0.25	0.5	1.0	1.5	2.0	2.5
Maximal relative eccentricity for cortical bone e_{1max}/D	0.24	0.23	0.23	0.22	0.21	0.20
Maximal relative eccentricity for trabecular bone e_{2max}/D	0.27	0.26	0.25	0.24	0.23	0.23
Maximal value of eccentricity for cortical bone e_{1max}, mm	9.77	9.5	9.08	8.71	8.40	8.12
Maximal value of eccentricity for trabecular bone e_{2max}, mm	10.9	10.6	10.1	9.68	9.3	9.0

Tab. 3. The calculated magnitudes of dimensional parameters for value of cortical bone elasticity modulus E_1=25 GPa

Name and identifier of dimensional parameter	Elasticity modulus of trabecular bone E_2, GPa					
	0.25	0.5	1.0	1.5	2.0	2.5
Maximal relative eccentricity for cortical bone e_{1max}/D	0.25	0.24	0.23	0.23	0.23	0.21
Maximal relative eccentricity for trabecular bone e_{2max}/D	0.27	0.27	0.26	0.25	0.24	0.23
Maximal value of eccentricity for cortical bone e_{1max}, mm	9.83	9.62	9.25	9.07	8.64	8.40
Maximal value of eccentricity for trabecular bone e_{2max}, mm	10.9	10.7	10.28	10.1	9.6	9.3

While analyzing the findings, we consider that $OK = e$; $OB = OA = R = 2e$ as it appears in Fig. 2b; i.e. maximum permissible distance from the center of section to the fixing screws installation points is equal to the doubled amount of eccentricity.

Since the fixing screws diameter is usually 8 mm (radius is 4 mm), maximum geometrically permissible distance from the center of bone cross-section to the fixing screws installation point without injury of the inner part of cortical layer with the screw thread (parameter Rmax) is Rmax =40/2-2-4=14 mm, providing that cortical layer thickness is 2 mm. Collation of this value with the maximum permissible values calculated on the basis of the data given in the Tabs. 1–3 points to secured provision of conditions for non-opening of junction in case of two-point asymmetric fixation with implant throughout the studied range of bone layers elasticity modules values variation.

The obtained date are based on approximate method of calculation and as result are approximate and estimate. But the accuracy of calculation used is sufficient for position determination of fixing screws' arrangement. More precise analysis of cortical and trabecular bones' stressed state is possible with using of numerical methods, e.g. FEM.

4. CONCLUSION

Methodology is suggested for calculation assessment of cortical and trabecular layer tension parameters in case of two-point asymmetric fixation with an implant for femoral neck fracture. It has been found that solid tightness of the broken parts against each other is secured over the whole fracture section without junction opening under condition that fixing screws are positioned in the trabecular layer without penetration of the thread side surface into cortical layer. This concerns the studied range of mechanical properties change of cortical and trabecular layers of bone tissue.

REFERENCES

1. **Akulich Yu.V., Nyashin Yu.I., Podgayets R.M., Dmitrenok I.A.** (2001), The bone tissue remodeling in the proximal femur under the variations of hip joint daily loading history, *Russian Journal of Biomechanics,* Vol.5, No.1, 12-23.
2. **Akulich, Yu.V. Denisov A.S.** (2008), Adaptivnyje izmenenija svojstv kostnoy tkani fragmentov kosti posle osteosynteza shejki bedra zhestkimi rezbovymi fixatorami, *Mehanika kompositsionnyh materialov i konstruktsyj*, Vol. 14, No.3, 313-331. (in Russian).
3. **Booth KC, Donaldson TK, Dai QG.** (1998), Femoral neck fracture fixation: a biomechanical study of two cannulated screw placement techniques / KC Booth, TK Donaldson, QG Dai, *Orthopedics*, 21, 1173–1176.
4. **Karev D.B.** (2012), Kontseptsyja osteosynteza v lechenii patsyjentov trudosposobnogo vozrasta s perelomom shejki bedrennoj kosti, *ARS MEDICA*, 4, 103-107 (in Russian).
5. **Manniger J., Bosch U., Cserhati P., Fekete K., Kazar G**. (2007), *Internal fixation of femoral neck fractures. An atlas*, Springer, Wien - New York.
6. **Minenkov B.V**., **Stasenko I.V**.(1977), *Prochnost detalej iz plastmass*. Moskva, Mashinostrojenije (in Russian).
7. *Spravochnik po soprotivleniju materialov* (1988) **Vinokurov Ye.F., Balykin M.K., Golubev A.I., et als**. – Minsk, Nauka i Tekhnika (in Russian).
8. **Van C.Mow, Rik Huiskes**. (2005), *Basic Ortopaedic Biomechanics and Mechano-Biology*, 3rd ed., Lipincott Williams @ Vilkins.
9. **Yeremin A.V.** (2010) Prochnostnyje harakteristiki gubchatoj kostnoj tkani krestsa i Lv pozvonka cheloveka *//Ukrainskij medychnyj almanah*, Vol. 13, No. 4, 83-84. (in Russian).