# *MATHEMATICAL MODELING OF DISTAL FEMUR MODULAR PROTHESIS REPLACEMENT*

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## Introduction

A great number of artificial constructions for bone defect replacements has been developed and is being introduced to medical practice today. Thus is a great need to study conditions of interaction of such constructions with the bone. The difficulty in solving this problem lies in the fact that it is impossible to study the state of the “implant – bone” system in experimental conditions. Modern possibility of mathematical modeling allows to practically solve the problem of permitted stress of bone tissue and implants for bone defect replacements, to find out the stresses which occur at the place of contact between biological and artificial tissues, etc. The finite element method is the most effective tool to solve such problems.

The main idea of the finite element method in solving marginal tasks is partial approximation of unknown functions. The area of a complex form is pictured as a sum of areas of a simple geometrical form (distal elements), and a number of basic functions (form functions) is entered to each of them.

To separate the areas of a complex form, the areas are divided into triangles (in flat areas) or tetrahedrons (in three-dimensional versions). The discovered functions are approximated in the element’s area by linear combinations of the form’s function. The functions are selected so that the values of the approximated functions on the element could be determined by the values of such functions or their derivative in a given number of points (nodular points), part of which is to be on the end of the element. The elements are joined together in these nodular points, which allows assembling them in a holistic finite element model of the construction.

In this way the task of determining the functions in the continual areas is accomplished by determining the discrete number of related values in nodular points of the finite element model of the construction. A particular function corresponds to each nodular variable. This function can be pictures as a coordinate to determine unknown values which represent solutions of marginal tasks.

**Objective of the study:** to study mechanical particularities of the interaction of the femur with a modular prosthesis used to replace is defects.

To reach the objective the following tasks were set:

- To study stress-deformity state of the construction and of the proximal part of the femur depending on the elevation angle of the intramedullar stem relating to the module of the construction;
- To study stress-deformity state of the construction and of the proximal part of the femur depending on the length of the intramedullar stem;
- To study stress-deformity state of the construction and of the proximal part of the femur depending on the height of the resection.

**Materials and Methods**

This study utilizes mathematical modeling with the help of the finite element method on the volumetric model of the femur. The model is built as a thee-dimensional object reflecting the anatomic particularities of the proximal and distal parts of the bone (the prototype was a lyophilized native male right femur – a teaching specimen). The model also reflected the anatomic particularities of the shaft of bone the presence of the "back crest" and "antecurvatio".

The model consisted of two parts 1 – external, which had mechanical characteristics of the cortical bone, 2 – internal, which had a shape of a low-pitched stem and characteristics of a trabecular bone (figure 1).

The distal part was removed from this model of the femur, and an implant was attached to the area of the removed bone for further research.

Figure 1 – Distal element femur model with implant

The models under research were divided into a certain number of distal elements. From 45 to 47 thousand standard distal elements are used in the given model. Each element has a certain number of levels of axial freedom according to which the COSMOS program determines the value of normal and tangential tensions for each joint and total stresses, and automatically calculates the factor of rigidity.

The construction was loaded in two areas: in the upper area (large swivel zone, small swivel zone, femur head), in the low area (lateral and medial bone zones). The load value on the femur head equaled 100 H and was directed perpendicular to the surface of the femur head (figure 2,b). The load value on the large swivel was 558 H and was directed at the 5° angle to the vertical from the load zone (figure 2,a). The load value on the small swivel was 280 H and was directed at the 35° angle to the vertical from the load zone.

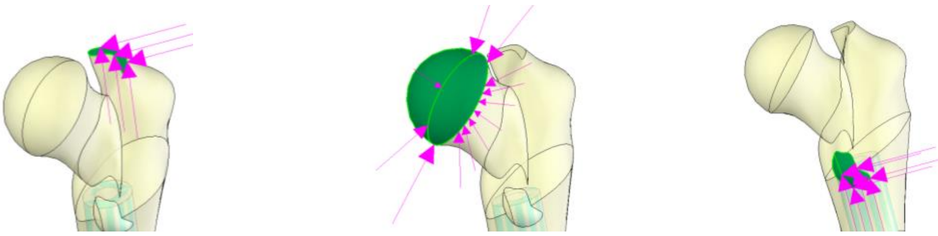



Figure 2 – Femur upper part load
a) large swivel, b) femur head, c) small swivel.

The load on the knee joined equaled 100 H, which were divided between the medial and lateral bones in the 1:2 ratio correspondently (figure 3).

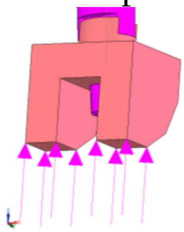


Figure 3 – Femur low part load

The bone tissue is received with the three orthogonal surfaces of the spring symmetry.

Mechanical characteristics of the materials used in the calculations were taken from the literature sources: bone tissue [1], implant characteristics [2].

**Table 1** – Mechanical characteristics of the materials used in the model

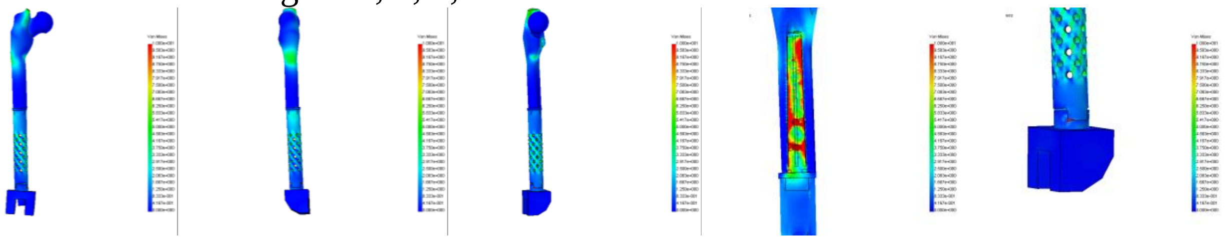
| Characteristics / Material | $E_x$ elasticity module, MPa | Puasson's coefficient |
|---|---|---|
| Cortical bone | 1500 | 0,29 |
| Trabecular bone | 500 | 0,3 |
| Titanium | $1{,}1*10^5$ | 0,2 |

**Results**

**1. The study of the stress-deformity state of the construction and of the proximal part of the femur depending on the elevation angle of the intramedullar stem relating to the module of the construction**

In order to study mechanical particularities of "implant – femur" system interaction we developed three versions on the model, which reproduce replacements of bone defects with implants at different angles between the upper and the middle parts of the implant. The study of the stress-deformity state of the models was conducted by four modes of loading: the angle between the femur axis and the stress line of the knee joint equaled 0, 30, 60 and 90 degrees. Such an approach allowed modeling the work of the knee joint in different positions (while walking, for example).

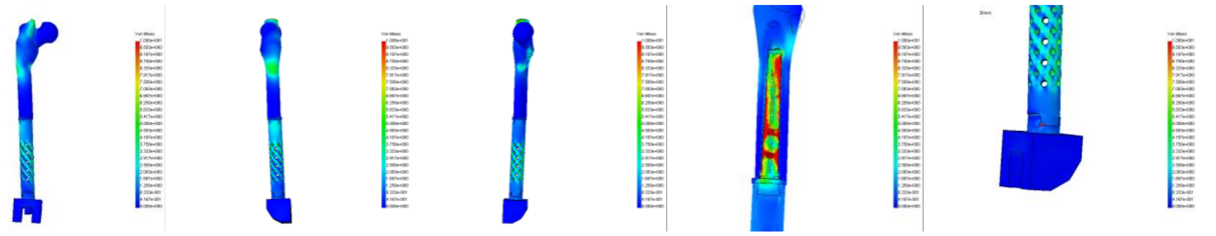
The results of the loading as well as of the distribution of the stress-deformity state of the model with the 0° elevation angle between the intramedullar stem and the implant module at the four above mentioned modes of the knee joint load are shown in figure 4, 5, 6, 7.



a) b) c) d) e)

Figure 4 – Distribution of the stress-deformity state of the model with the 0 degrees elevation angle between the upper and the middle parts of the implant and with the 0 degrees angle between the femur axis and load line of the knee joint

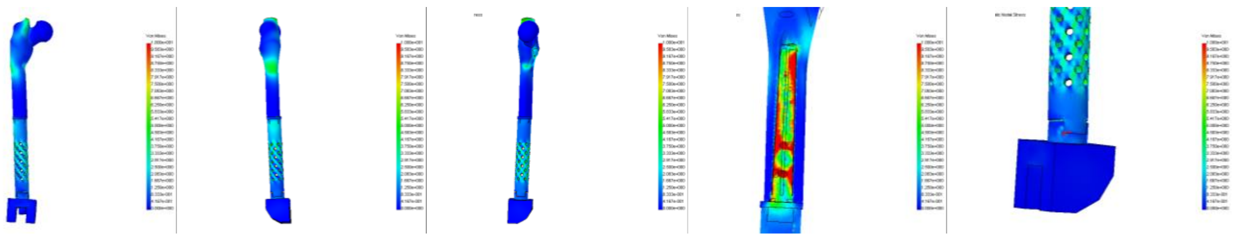
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model



a) b) c) d) e)

Figure 5 – Distribution of the stress-deformity state of the model with the 0 degrees elevation angle between the upper and the middle parts of the implant, and the 30 degrees angle between the femur axis and the knee joint stress line

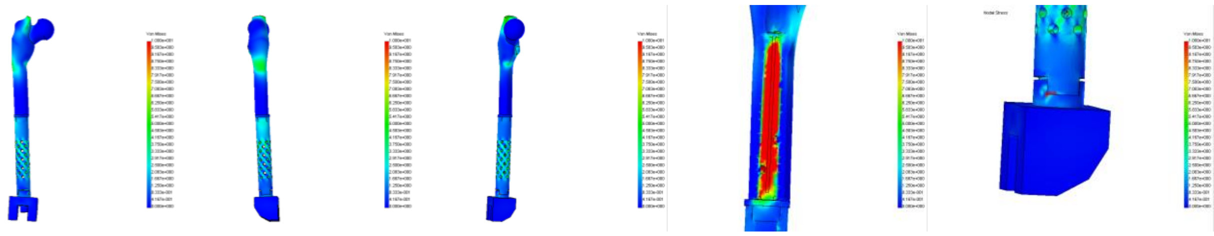
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model



a) b) c) d) e)

Figure 6 – Distribution of the stress-deformity state of the model with the 0 degrees elevation angle between the upper and the middle parts of the implant, and the 30 degrees angle between the femur axis and the knee joint stress line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) of the Maximum stress zone on the outer surface model



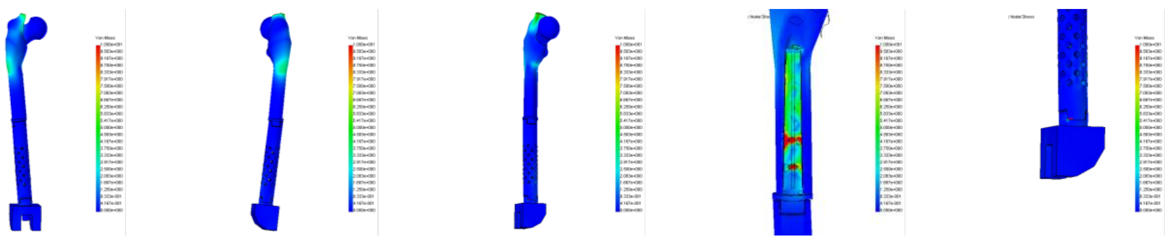
a) b) c) d) e)

Figure 7 – Distribution of the stress-deformity state of the model with the 0 degrees elevation angle between the upper and the middle parts of the implant, and the 90 degrees angle between the femur axis and the knee joint stress line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model

Analysis of data received concerning the first model (with the 0° angle between the upper and middle parts of the implant) revealed that the change of the load angle on the femur component of the knee joint does not cause the change of maximum load zones in each element of the construction (figure 4.a,b,c; 5.a,b,c; 6.a,b,c; 7.a,b,c). Only the maximum load value changes significantly (from 131,9 MPa with the 30° knee joint load angle to 264,4 MPa with the 90° knee joint load angle) in the intramedullar stem of the implant, which is located around the locking screws (figure 4.d, 5.d, 6.d, 7.d). Large loads are also located along the entire length of the stem. The maximum stress zone for the middle part of the implant is always located in the medial part of the construction (figure 4.e, 5.e, 6.e, 7.e). Stress concentration in this area is explained by the fact that the construction of the connecting joint has a rectangular look. It is possible to solve this problem by eliminating sharp angles (for example, by making a cone-shaped connecting joint).

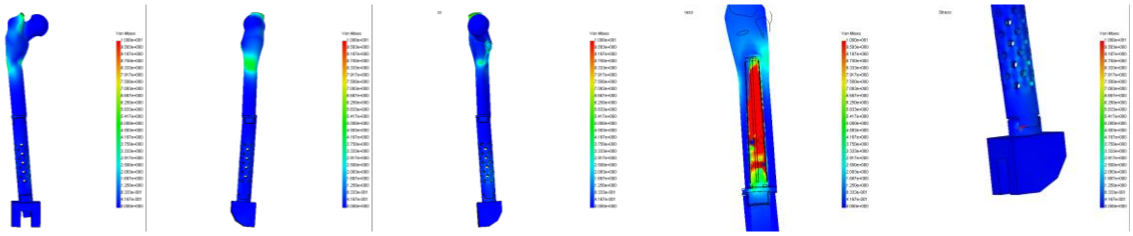
The results of the loading and the distribution of the stress-deformity state of the model with the 2° elevation angle between the intramedullar stem and the implant module, and at the four above-mentioned modes of the knee joint loading, are shown in figure 8, 9, 10, 11.



a) b) c) d) e)

Figure 8 – Distribution of the stress-deformity state of the model with the 2 degree elevation angle between the upper and the middle parts of the implant and the 0 degree angle between the femur axis and the knee joint load line

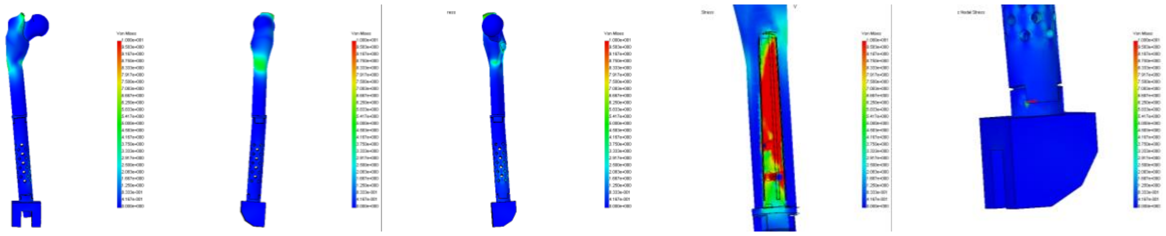
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model



a) b) c) d) e)

Figure 9 – Distribution of the stress-deformity state of the model with the 2 degree elevation angle between the upper and the middle parts of the implant and the 30 degree angle between the femur axis and the knee joint load line

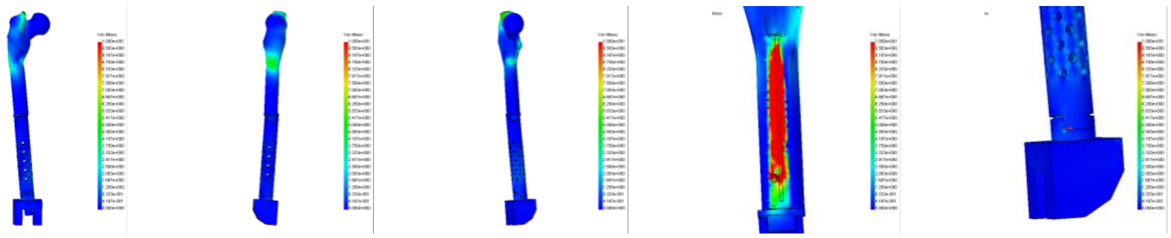
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model



a) b) c) d) e)

Figure 10 – Distribution of the stress-deformity state of the model with the 2 degrees elevation angle between the upper and the middle parts of the implant and the 60 degrees angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model



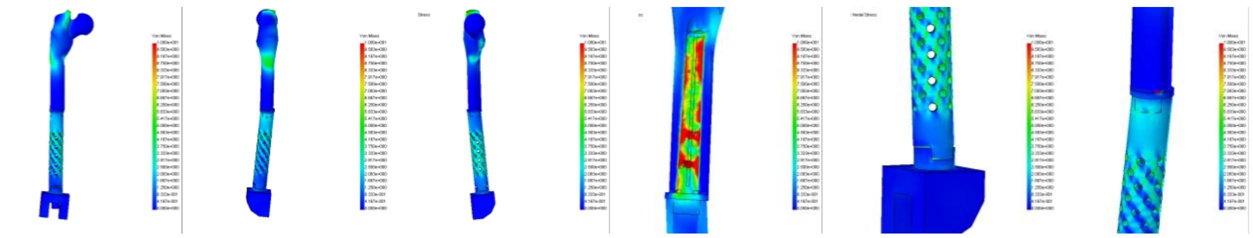
a) b) c) d) e)

Figure 11 – Distribution of the stress-deformity state of the model with the 2 degrees elevation angle between the upper and the middle parts of the implant and the 90 degrees angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model

Data analysis received from the second model (with the 2° angle between the upper and the middle parts of the implant) demonstrated that the change in the load angle on the femur component of the knee joint does not lead to the change of the maximum load zones in each element of the construction either (figure 8.a,b,c; 9.a,b,c; 10.a,b,c; 11.a,b,c). A significant change occurs only in the maximum load value in the intramedullar stem of the implant (from 118,4 MPa at 30° and 90° knee joint load angles to 248 MPa at 60° knee joint load angle), which is located around the locking screws (figure 8.d, 9.d, 10.d, 11.d). Large loads are also distributed along the entire length of the stem. However, unlike the previous model, the change of the load angle causes rather large fluctuations of the maximum load value in the process of change of the knee joint load angle. The maximum stress zone for the middle part of the implant is always located in the low medial part (pic. 8.e, 9.e, 10.e, 11.e).

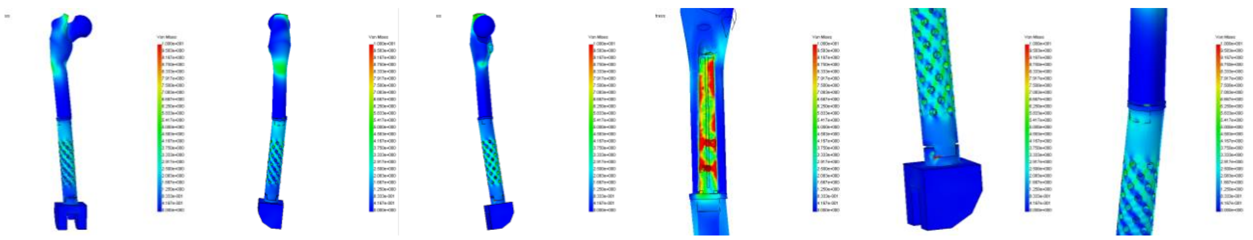
The results of the load and the distribution of the stress-deformity state of the model with the 5° elevation angle between the intramedullar stem and the implant module, and at the four above-mentioned modes of the knee joint loading, are shown in figure 12, 13, 14, 15.



a) b) c) d) e) f)

Figure 12 – Distribution of the stress-deformity state of the model with the 5 degrees elevation angle between the upper and the middle parts of the implant and the 0 degrees angle between the femur axis and the knee joint load line

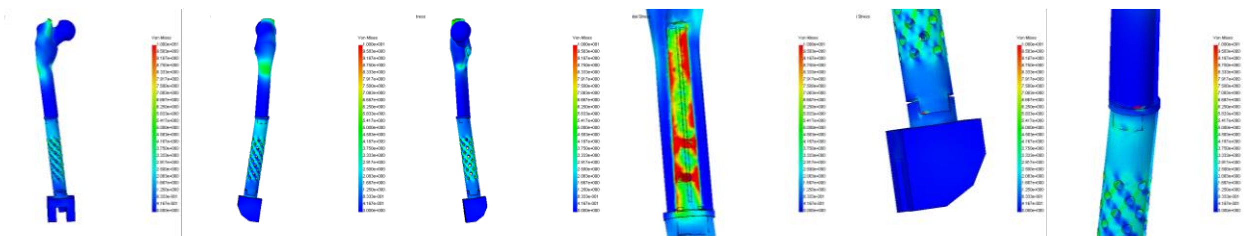
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model (medial area); f) Maximum stress zone on the outer surface of the model (lateral area)



a) b) c) d) e) f)

Figure 13 – Distribution of the stress-deformity state of the model with the 5 degrees elevation angle between the upper and the middle parts of the implant and the 30 degrees angle between the femur axis and the knee joint load line

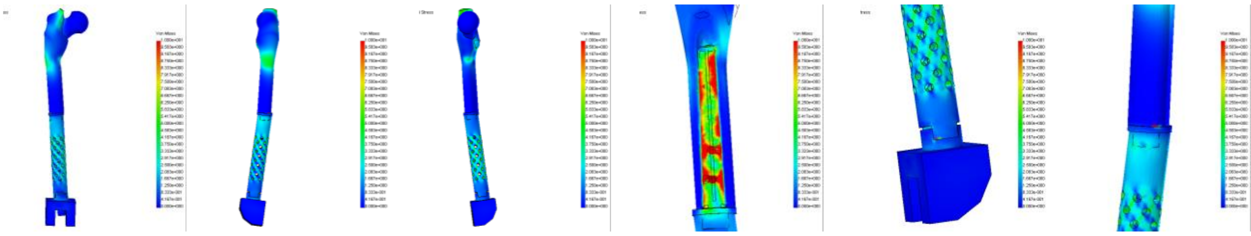
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model (medial area); f) Maximum stress zone on the outer surface of the model (lateral area)



a) b) c) d) e) f)

Figure 14 – Distribution of the stress-deformity state of the model with the 5 degrees elevation angle between the upper and the middle parts of the implant and the 30 degrees angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model (medial area); f) Maximum stress zone on the outer surface of the model (lateral area)



a) b) c) d) e) f)

Figure 15 – Distribution of the stress-deformity state of the model with the 5 degrees elevation angle between the upper and the middle parts of the implant and the 90 degrees angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface; e) Maximum stress zone on the outer surface of the model (medial area); f) Maximum stress zone on the outer surface of the model (lateral area)

Data analysis received from the second model (with the 2° angle between the upper and the middle parts of the implant) demonstrated a significant change in the maximum load value in the implant stem around the openings. Large loads are also distributed along the entire length of the stem (figure 12.d, 13.d, 14.d, 15.d). However, unlike the two previous models, the change of the load angle practically does not cause the fluctuation of the maximum load value (it changes from 208,4 – 211 MPa at 90° knee joint load angle). For the middle part of the implant, there are already two zones where large stresses accumulate. These are the zones of the upper lateral and low medial parts (figure 12.e,f; 13.d,f; 14.d,f; 15.d,f). Besides that, there appears a zone of additional stresses on the contact line between the bone and the construction, where the stress value grows to 20 MPa comared to 5 MPa with the 0 - 2° elevation angles between the intramedullar stem and the module.

Therefore we can reach a conclusion that the angle between the femur axis and the knee joint load line does not effect the character of the stress distribution in the implant stem (table 2), or the place of the maximum stress zone in the middle part of the implant. However it is necessary to observe that every intramedullar stem elevation angle has its own mechanical particularities.

**Table 2** – Value of maximum stresses in the implant stem (MPa)

| Angle between femur axis and knee joint load line | Angels between upper and middle parts of the implant | | |
|---|---|---|---|
| | 0 degrees | 2 degrees | 5 degrees |
| 0 degrees | 132,29 | 218,07 | 211,06 |

| | | | |
|---|---|---|---|
| 30 degrees | 131,82 | 118,40 | 208,38 |
| 60 degrees | 240,27 | 247,94 | 210,81 |
| 90 degrees | 264,42 | 118,39 | 226,98 |

Figure 16 provides a better view on the stress changes in the intramedullar stem depending on its angle to the module, as well as on the knee joint load angle.

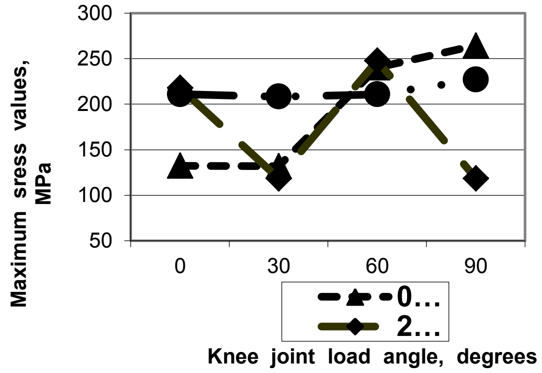



Figure 16. – Diagram of the relation of the maximum stress value to the angle between the femur axis and the knee joint load line

The diagram indicates that the maximum stress values do not significantly differ depending on different angles of the stem (227 - 264,4 MPa). However at the 0° degree of the stem there observed a leaping change in the stress values almost in two times. At the 2° intramedullar stem elevation, the stress value grows to the maximum with the 0 and 30° knee joint load angles, and decreases to the minimum with the 60° and 90° knee joint load angles. At the 5° intramedullar stem elevation, the stress value practically levels. However such a construction causes stress picks in the bone tissue on the “implant – bone” line.

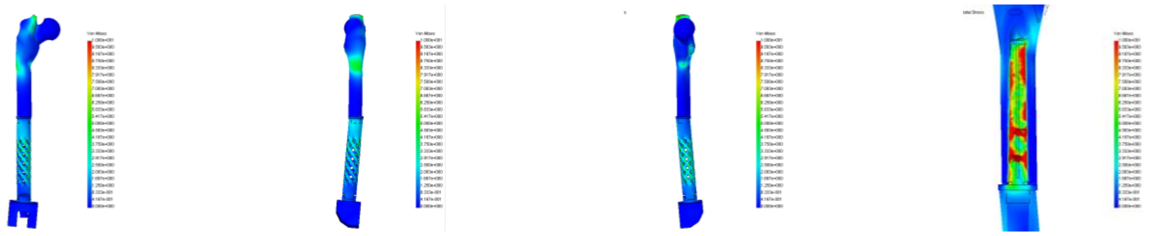
Therefore we can conclude that the intramedullar stem elevation angle should not be more than 5°. However the selection of its angle depends, in a greater degree, on the anatomical particularities of the patient’s femur.

**2. The study of the stress-deformity state of the construction and of the proximal part of the femur depending on the length of the intramedullar stem**

As a next stage, we developed two versions of the model, which reproduced the bone defect replacement with the implants with different stem length. We studied the models with 80, 110 and 140 mm intramedullar stem length. We conducted the study of the stress-deformity state of the models which were loaded in four ways: the angle between the femur axis and the knee joint load line was 0, 30, 60 and 90 degrees.

The results of the loading and the distribution of the stress-deformity state of the model with the 5° elevation angle between the intramedullar stem and the implant module, at the four above-mentioned ways of loading of the knee joint, and with the 110 mm stem length, are shown in figure 12, 13, 14, 15, and are thoroughly described in the previous chapter.

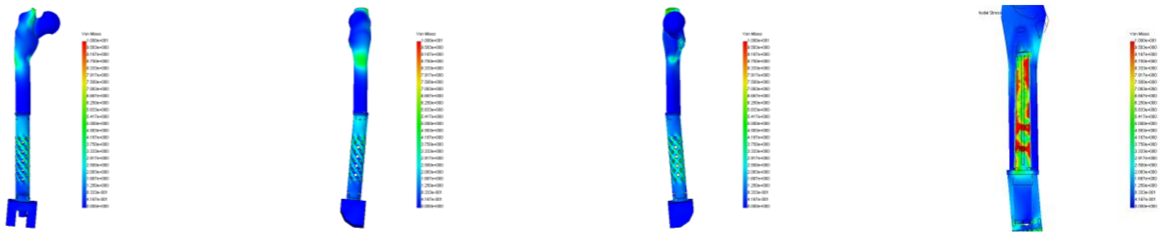
The results of the loading and the distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, and with the 80 mm stem length, are shown in figure 17, 18, 19, 20.



a) b) c) d)

Figure 17 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 80 mm stem length, and the 0° angle between the femur axis and the knee joint load line

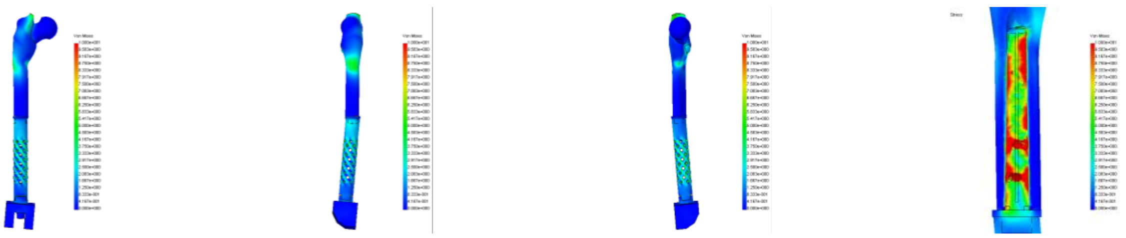
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface



a) b) c) d)

Figure 18 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 80 mm stem length, and the 30° angle between the femur axis and the knee joint load line

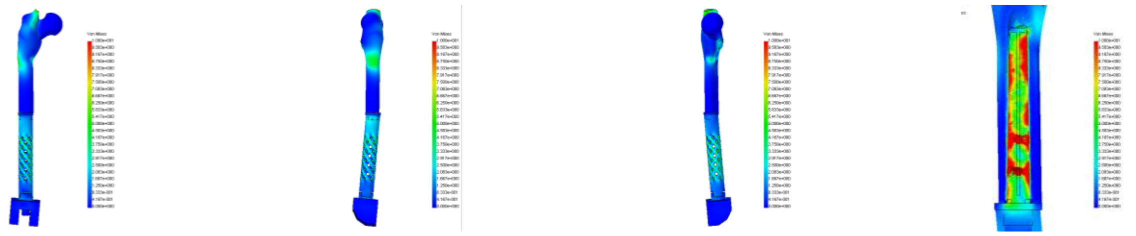
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface



a) b) c) d)

Figure 19 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 80 mm stem length, and the 60° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface



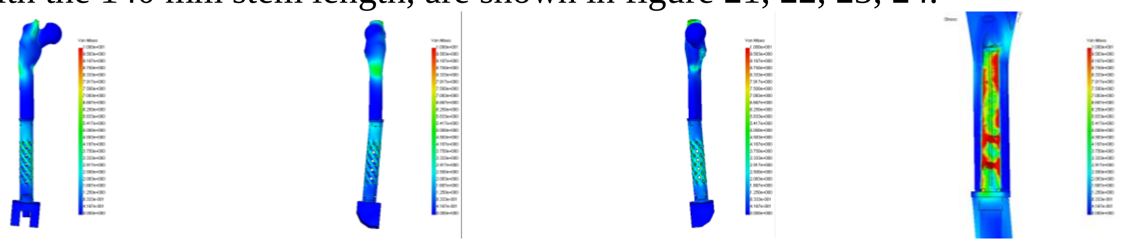
a) b) c) d)

Figure 20 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 80 mm stem length, and the 90° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface

Data analysis received from the study revealed that the decrease of the stem length causes additional large stress zones to appear in the upper lateral part of the femur, above the end of the intramedullar stem, and that the value of maximum stresses significantly increases in the stem compared to the 110 mm stem (828 MPa and 227 MPa respectively) (table 3, figure 17, 18, 19, 20).

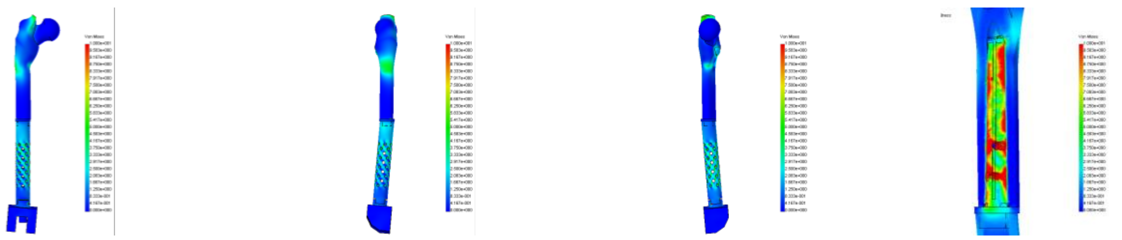
The results of the loading and the distribution of the stress-deformity state of the model with the 5° elevation angle between the intramedullar stem and the implant module, at the four above-mentioned ways of loading of the knee joint, and with the 140 mm stem length, are shown in figure 21, 22, 23, 24.



a) b) c) d)

Figure 21 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 140 mm stem length, and the 0° angle between the femur axis and the knee joint load line

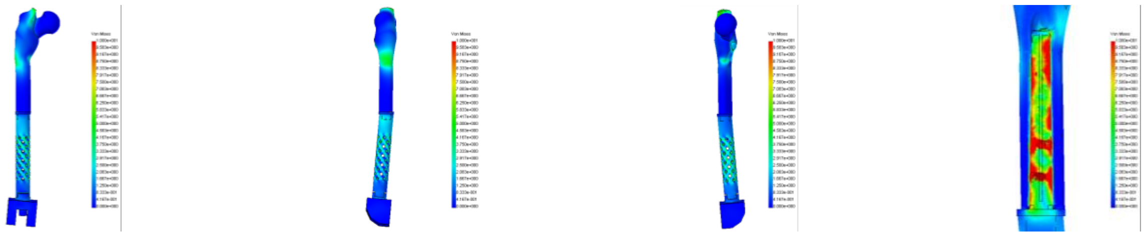
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface



a) b) c) d)

Figure 22 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 140 mm stem length, and the 30° angle between the femur axis and the knee joint load line

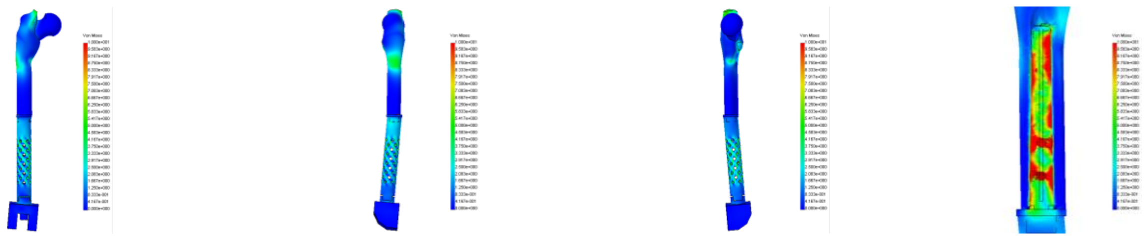
a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface



a) b) c) d)

Figure 23 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 140 mm stem length, and the 60° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface



a) b) c) d)

Figure 24 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 140 mm stem length, and the 90° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view; c) sagittal view; d) intersection along the sagittal surface

Data analysis received from the study revealed that the increase of the stem length causes the decrease of the stem load and the shaft of the femur bone. However the location of the stem's end in the intertrochanteric zone causes the redistribution of stresses in the area of the great trochanter (7 MPa compared to 1,5 MPa in shorter stems), which in its turn, could cause the deformation of the hip joint on the whole.

**Table 3** – Maximum stresses value in the implant stem (MPa)

| Angle between femur axis and knee joint load line | Stem length | | |
|---|---|---|---|
| | 80 mm | 110 mm | 140 mm |
| 0 degrees | 544,90 | 211,06 | 144,57 |
| 30 degrees | 374,60 | 208,38 | 139,80 |
| 60 degrees | 358,94 | 210,81 | 135,00 |
| 90 degrees | 828,19 | 226,98 | 155,89 |

Figure 25 provides a diagram of the correlation between maximum loads in the itramedullar stem of different length depending on the knee joint load angle.

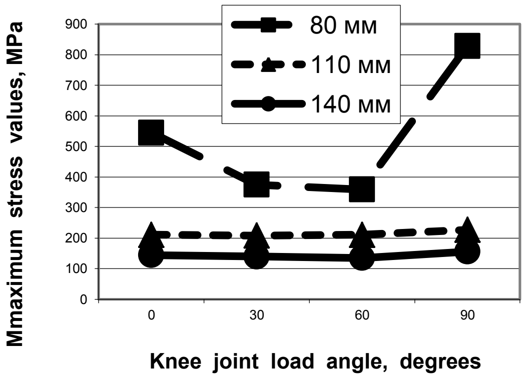



Figure 25 – Diagram of the correlation of the maximum stress value and the stem length

As the diagram indicates, the stress value in the intramedullar stem increases with the decrease of its length. However, while choosing the stem length in each case, it is necessary to make sure that its end does not get into the intertrochanteric zone, because in this case, according to our study, there can be certain complications with the condition of the bone tissue in the area of the large swivel.

**3. The study stress-deformity state of the construction and of the proximal part of the femur depending on the length of the resection**

As the next stage, we developed two models, which reproduced the replacement of the bone defect with implants with different module length. We studied the models with 96, 196 and 296 mm module lengths. We studied the stress-deformity state of the models, which were loaded in four ways: the angle between the femur axis and the knee joint load line was 0, 30, 60 and 90 degrees.

The results of the loading and the distribution of the stress-deformity state of the model with the 5° elevation angle between the intramedullar stem and the implant module, at the four above-mentioned ways of loading of the knee joint, and with the 196 mm module length, are shown in figure 12, 13, 14, 15 and are thoroughly described in the previous chapter.

The results of the loading and the distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant and the 96 mm itramedullar stem length are shown in figure 26, 27, 28, 29.

a) b)

Figure 26 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 96 mm module length, and the 0° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

a) b)

Figure 27 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 96 mm module length, and the 30° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

a) b)

Figure 28 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 96 mm module length, and the 60° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

a) b)

Figure 29 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 96 mm module length, and the 90° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

Data analysis received from the study reveals that the change of the length of the module causes large stress zones to appear in the lateral part of the femur (15 MPa in the bone tissue and 1182 MPa in the low part of the intramedullar stem), which can even lead to the destruction of the middle part of the femur (figure 26, 27, 28, 29) or intramedullar stem fracture.

The largest stress value in the intramedullar stem appears at the 60° angle of the knee joint load (1182 MPa), and the smallest value – at the 30° angle (412 MPa).

It may be explained by the fact that we changed the anatomic characteristics of the femur when constructing this model.

The results of the loading and the distribution of the stress-deformity state of the model with the 5° elevation angle between the intramedullar stem and the implant module, at the four above-mentioned ways of loading of the knee joint, and with the 296 mm stem length, are shown in figure 30, 31, 32, 33.

a) b)

Figure 30 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 296 mm module length, and the 0° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

a) b)

Figure 31 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 296 mm module length, and the 30° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

a) b)

Figure 32 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 296 mm

module length, and the 60° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

a) b)

Figure 33 – Distribution of the stress-deformity state of the model with the 5° elevation angle between the upper and the middle parts of the implant, 296 mm module length, and the 90° angle between the femur axis and the knee joint load line

a) front view; b) sagittal view;

As the study results revealed, the increase of the module length up to 296 mm causes the decrease in minimal values of stress in the itramedullar stem to 112 MPa, and such values are observed with all knee joint load angles. It is necessary to note that with the given resection height the maximum load zone shifts to the endoprosthesis module, and the bone tissue stress in the femoral bone diaphysis significantly decreases (0,4 MPa compared with 15 MPa with the 96 mm module length). It however revealed a stress concentration in the large swivel area, which is caused by the itramedullar stem entering the intertrochanteric zone. Therefore while selecting the endoprosthesis construction to replace the defects of the upper third of the femoral bone, it is necessary to choose the length of the intramedullar stem so that it does not enter the intertrochanteric zone and has a sufficient length.

The indicated maximum load values for each model at different knee joint load angles allow to compare mechanical particularities of the interaction of the "endoprosthesis – femoral bone" system depending on the resection height (table 4).

**Table 4** – Maximum stress value in the implant stem (MPa)

| Angle between femur axis and knee joint load line | Module length | | |
|---|---|---|---|
| | 96 mm | 196 mm | 296 mm |
| 0 degrees | 575,42 | 211,06 | 111,66 |
| 30 degrees | 412,42 | 208,38 | 111,91 |
| 60 degrees | 1182,50 | 210,81 | 112,09 |
| 90 degrees | 898,67 | 226,98 | 112,05 |

Figure 34 provides a diagram of correlation of maximum stresses in the intramedullar stem of different length depending on the knee joint load angle.

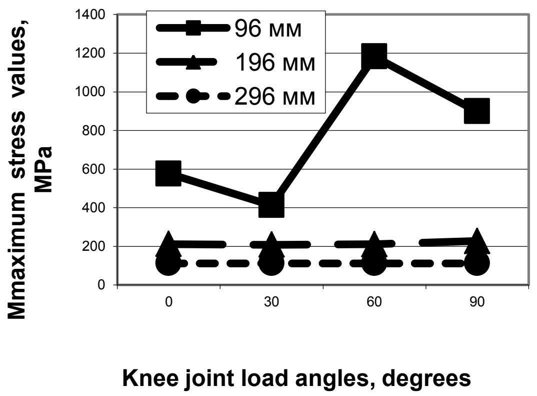



Figure 34 – Diagram of dependence of maximum stress value from the stem length

As the diagram indicates, significant increase of stresses both in the intramedullar stem and in the bone diaphysis are observed in the low third at the diaphysis resection of femur. They reach close to critical values (1182 MPa). Femur resection at the middle or upper thirds of the femur leads to a general decrease of stresses regardless of the knee joint load angle (227 and 112 MPa with the 196 mm and 296 mm module length respectively), due to the shift of the maximum stress zone from the bone tissue to the endoprosthesis module. Such results can be explained by the fact that the resection of the femur is made lower than the top of the anatomic curve of the bone with the 96 mm module length. An effort to implant the streight itramedullar stem into the most curved part of the bone creates additional stresses. Regardless of the fact that the lowest stress (112 MPa) is observed at the resection of the femur at the upper third, the concentration of maximum stresses in the large swivel zone caused by the intramedullar stem entering the itertrochanter zone, can be considered a negative.

**Summary**

Therefore the following conclusions can be made following the results of the study:

- The largest stresses in the work of the construction appear along the entire length of the stem, with maximum values in the locking screws area, in the foundation of the intramedullar stem and in the connecting joint angles of the endoprosthesis module with the intramedullar stem and the joint element;
- Stresses which appear in metal constructions are not critical;
- At the 5° elevation angle between the intramedullar stem and the endoprosthesis module a concentration of stresses in the bone tissue in the resection area is observed;
- The angle between the implant’s middle part axis and the stem must be individually chosen for more optimal construction performance (within 0 – 1 degrees, or 3 – 4 degrees), as there appear additional variable stresses while walking which could lead to the destruction of the construction. Such situations are possible.

- The stress value which appears in the itramedullar stem is inversely proportional to its length;
- If the end of the intramedullar stem enters the itertrochanter area, a concentration of stresses on the large swivel is observed;
- The following should be considered in selecting the length of the stem: its leg should not be shorter than 100 mm, and the leg's end should not be located in the itertrochanter area;
- A significant increase of stresses is observed at the femur diaphysis resection in both intramedullar stem and the bone diaphysis, which reach next to critical values. As a result the femur resection is made lower than the top of the anatomic curve of the bone. Implanting the streight intramedullar stem into the most curved part of the bone causes additional stresses to appear;
- Femur resection on the level of the middle and the upper thirds leads to general decrease of stresses regardless of the knee joint load angle due to the shift of the maximum stress zone from the bone tissue to the endoprosthesis module.

**References**

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**Abstract**

**Introduction:** Implant failure is the most frequent complication after surgery for large bone defect. Mathematical modelling and finite element method allow and show the mechanical features of the interaction between femoral bone and endoprosthesis after distal femur replacement. The stressedly-deformed condition of the distal femur endoprosthesis depends on the angle of inclination and the length of intramedullary stem and the level of the femoral bone resection.

**Material and method(s):** The finite element method for three-dimensional model of the femur was used. This model was created in the form of 3D object with the reconstitution of anatomical features of the proximal and distal ends of femoral bone. The prototype was the teaching specimen as a freeze-dried native male right femur. The model reproduces of anatomic features of the bone shaft - back crista and antecurvation. There are two parts: the first one (external) had mechanical properties of cortical bone, the second one (internal) had characteristics of trabecular bone and had form of a hollow rod. For further studies distal end of the femur model was removed and bone defect was replaced by implant. Three variants of the model have been developed to study the mechanical features of implant-femur interaction. The models reproduced bone defect replacement by implants with different values of inclination angle between the upper and middle parts of the implant. Investigation of the stressedly-deformed condition was realized under load bearing with 0°, 30°, 60° and 90° of the inclination angles between hip and knee joints load lines. Intramedullary stem lengths were 80, 110 and 140 mm and the lengths of prosthesis body were 96, 196 and 296 mm as well.

**Result(s) and Conclusion(s):**

Maximum stresses arise in the intramedullary stem along its entire length and load peak is localized in the base of intramedullary stem. The bone resection stress concentration is observed in 5° inclination angle of intramedullary stem and the endoprosthesis body. The angle between  implant body and stem has to be selected individually in the range from 1 to 4 degrees for optimum performance. Stress rate is inversely proportional to the stem lenght. Stress rate is observed in great trochanter zone when the end of the intramedullary stem is in intertrochanteric area. The prosthesis stem should not be shorter than 100 mm. The end of it should not be placed in the intertrochanteric area. Significant increase stress rates in intramedullary stem and femoral shaft are observed with the distal third resection of the femoral bone. Zone of maximum stress rates moves from bone shaft to prosthesis body when level of femur resection is on upper and middle thirds of it. It drives to the overall reduction of stress rates regardless of weigh bearing angle of knee joint.