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Stem neck-shaft angle as a biomechanical prerequisite for aseptic loosening of the acetabular component (experimental study)

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Abstract

Introduction Causes of aseptic loosening of THA components and improvement of the implants remain the subject of scientific discussions. **The objective** was to perform comparative analysis of the results of biomechanical modeling of cementless total hip arthroplasty using implants with different stem neck-shaft angles as a prerequisite of aseptic loosening of the acetabular component. **Material and methods** A biomechanical model of the pelvis and an implant with different stem neck-shaft angles was constructed based on computed tomography findings. Stresses and strains that the patient typically experienced under full weight-bearing on the operated lower limb were explored. Results The use of a stem neck-shaft angle of 125° provided the most favorable localization of the contact patch at the border of the acetabular component – the pelvic bone and lower values of equivalent stresses and contact pressure in comparison with more "valgus" femoral components (135° and 145°). **Discussion** The data obtained were fully consistent with the results of biomechanical studies by L. Quagliarella et al. (2006) who reported the substantial significance of the neck-shaft angle for on the parameters of contact pressure, since wear and debris-associated osteolysis decrease with a decreased neck-shaft angle. The use of stem neck-shaft angles equal to 125° can be indicated for young patients with good bone quality and equal lower limb length. Unstable femoral cup can be caused by eccentric position of the contact spot at the border of the bone and the acetabular component and distribution of contact pressure and equivalent stresses inside the spot that are typical for artificial joints with stem neck-shaft angle of 145°. **Conclusion** The findings suggested that the value of stem neck-shaft angle was likely be considered a prerequisite for aseptic loosening of the acetabular component.

Keywords: biomechanics, biomechanical modeling, finite element method, total hip arthroplasty, aseptic loosening, equivalent stresses, contact pressure

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INTRODUCTION

Surgical treatment of patients with aseptic loosening of total hip arthroplasty (THA) is one of the cornerstones of modern orthopaedics. Despite significant differences in revision operations and the dependence on many factors, aseptic loosening of endoprosthetic components and osteolysis are the most common reasons for repeated surgical interventions [1]. Improvement of biomechanical characteristics and implant design facilitate reduction in revision total joint arthroplasties and increased lifetime of the artificial joint after primary total joint replacement [2]. N. Ramaniraka et al. (2000) suggested that the THA should be maximally adapted to the individual anatomy of a particular patient with the restored hip functions being close to physiological. and the quality of primary fixation and osteogenetic processes at the implant-bone interface have a great influence on the implant lifetime [3].

Femoral components with valgus stem neck-shaft angle are traditionally used to reduce eccentric bending loads to the endoprosthetic stem [4]. C. Shidlo et al. (1999) reported the stem neck-shaft angle of artificial joint is greater by 18° than the individual anatomical values of the patient's neck-to-shaft angle [5]. A limb length discrepancy can be observed after THA [6-8]. The researchers examined various combinations of geometrical parameters of the femoral component (neck-shaft angle, anteversion, neck length) that are responsible for distribution of stresses and contact pressure at the interface between the acetabular component and the bone. The authors concluded that the magnitude of the anteversion of the stem of the artificial joint has a significant effect on the stress and strain parameters of the contact pair.

L. Quagliarella et al. (2006) performed a three-stage biomechanical study based on the three-dimensional model of A. Iglič et al. (2002) [9], the own finite element model and cup contact pressure measured with the method developed by A. Strozzi et al. (1999) [10] to evaluate the effect of the geometrical parameters of the endoprosthetic stem on distribution of stresses in the neck of the femoral component and characteristics of the contact pressure at the cup-bone interface [1]. The author suggested that with increased neck-shaft angle, the stresses in the neck decreased and the contact pressure increased. The neck-shaft angle could affect the implant stability, since the use of more varus stems would help reduce contact pressure and wear [1].

The objective was to perform comparative analysis of the results of biomechanical modeling of cementless total hip arthroplasty using implants with different stem neck-shaft angles as a prerequisite of aseptic loosening of the acetabular component.

MATERIAL AND METHODS

A solid three-dimensional geometric model of the pelvis was constructed based on the computed tomography (CT) of a particular patient, processed with the Mimics software package. Then the 3Matic program was used. Virtual solid models of a cementless hip implant with a wedge-shaped stem of three types were constructed with neck-shaft angles of 125°, 135° and 145° based on relevant implants. Using the SolidWorks computer-aided design system, the constructed models of the endoprosthetic hip were placed in the pelvis model according to the generally accepted technology for the implantation used in surgical practice (location of the acetabular component in the anatomical center of rotation with 45° inclination, 15° anteversion and full coverage; location femoral component with 10° anteversion). Three solid three-dimensional models of the pelvis were obtained for cementless THA using different neck-shaft angles of the femoral component. The diameter of the acetabular component was 50 mm, the diameter of the head was 28 mm in all models. The Ansys 19.0 system was used for loading finite element models. A static problem of solid mechanics was solved for each model [12]. As boundary conditions, an axial load corresponding to the weight of a person at two-support standing was applied to the constructed model (a load of 450 N was applied to the endoprosthetic stem) with the iliac crest being rigidly fixed (Fig. 1).

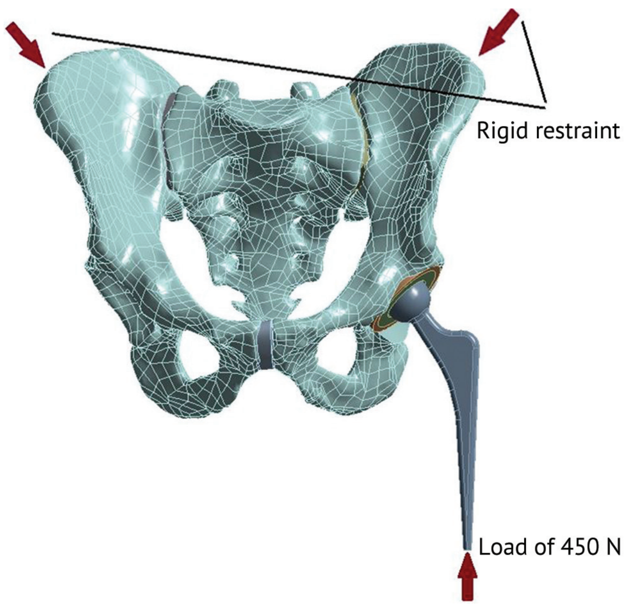

Fig. 1 Boundary conditions

All materials were considered ideally elastic and isotropic. The properties of the materials are presented in Table 1. Young's modulus of spongy bone was calculated individually based on CT data using the technique developed [13]. The properties of other materials presented in Table 1 were taken in the literature [11, 12].

Table 1

Mechanical properties of pelvic tissues and implant materials

Material	Young's modulus, MPa	Poisson's ratio
Cortical bone	11000	0.3
Cancellous bone	200	0.3
Ligament	50	0.4
Endoprosthetic liner (polyethylene)	1100	0.33
Titanium alloy	96000	0.36

With the complex geometry of the pelvic model, an irregular tetrahedral computational grid was created to calculate the parameters of the stress-strain (Fig. 2). A more dense hexahedral and computational mesh was created on endoprosthetic models to obtain simulation results that would depend little on the size.

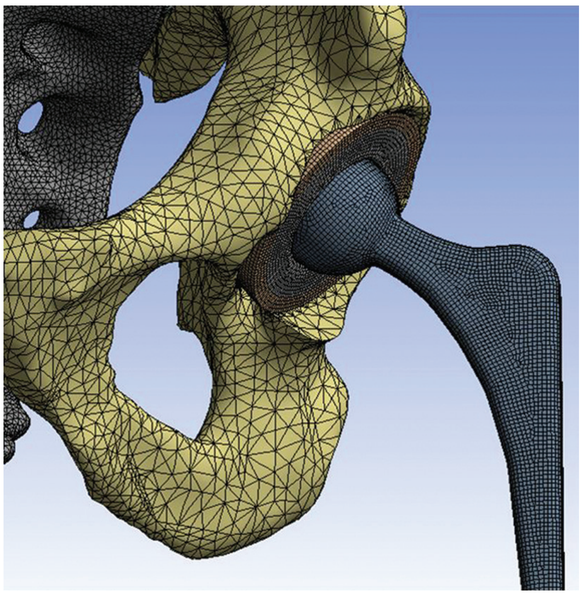

Fig. 2 Computational grid

Results of biomechanical modeling were compared with the results of clinical and additional instrumentation studies of patients after primary THA at a late follow-up.

RESULTS

Fields of displacements and equivalent stresses were calculated in models with different neck-shaft angle of the wedge-shaped femoral component. Typical fields of total displacements and equivalent stresses are shown in Fig. 3.

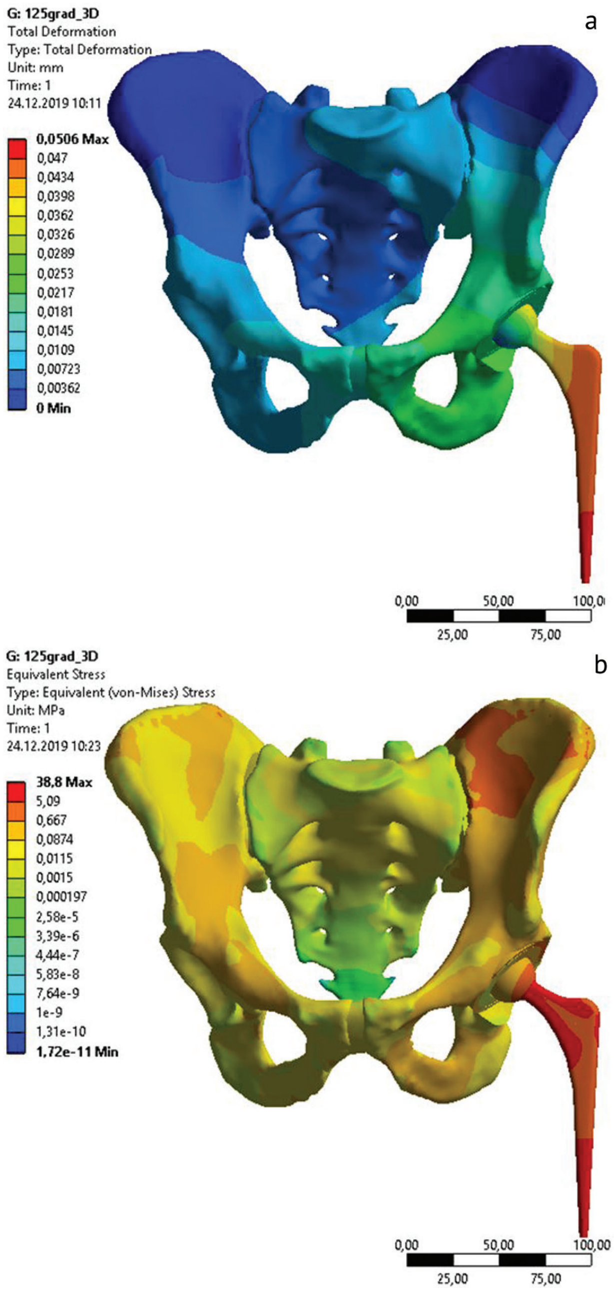

Fig. 3 Typical fields of total displacements (a) and equivalent stresses (b) in models of pelvic systems used for cementless THA with neck-shaft angle of the femoral component measuring 125°

Characteristics of equivalent stresses arising in a polyethylene liner were shown to be indicative (Table 2). Equivalent stresses was 1.3 MPa for models with a neck-shaft angle of 125°, 2.7 MPa for 135°, and 4.8 MPa for 145°. These data indicate an inevitable increase in the load on the liner with stems with larger neck-shaft angles.

Table 2

Equivalent stresses in the liner and contact pressure between the liner and the endoprosthesis head

Neck-shaft angle of the femoral component	Equivalent stresses, MPA	Contact pressure, MPa
125°	1.3	1.2
135°	2.7	2.6
145°	4.8	4.5

The analysis of the contact pressure values between the head of the artificial joint and the surface of liner correlated with the values of equivalent stresses in it. The values of the parameter were minimum and amounted to 1.2 MPa with the use of the femoral component with neck-shaft angle of 125° and measured 2.6 and 4.5 MPa for stems with 135° and 145° neck-shaft angle, respectively. The equivalent stresses arising on the surface of the bone bed in contact with the surface of the acetabular component were measured. Maximum equivalent stresses at the pelvic-cup interface measured 0.56 Mpa for models with a femoral component having a neck-shaft angle of 125°. Similar values of the parameter for endoprostheses with stems of 135° and 145° were equal to 0.6 and 1.5 MPa, respectively (Table 3).

Table 3

The maximum equivalent stresses and contact pressure on the contact surface of the endoprosthesis cup and bone

Neck-shaft angle of the femoral component	Equivalent stresses, MPA	Contact pressure, MPa
125°	0.56	0.83
135°	0.60	0.84
145°	1.50	1.60

Correlation of the contact pressure and the cup of the endoprosthesis on the surface of the bone bed on the neck-shaft angle of the stem indicated an increased values of the characteristics with implantation of more "valgus" femoral components. The contact pressure was 0.83 MPa with endoprosthetic stem with neck-shaft angle of 125°, 0.84 MPa with neck-shaft angle of 135° and increased to 1.60 MPa with a femoral component with neck-shaft angle of 145°. The analysis of the data indicated a spasmodic increase in the values of equivalent stresses and contact pressure on the pelvic bone at the border of the acetabular component of the implant with use of a stem with neck-shaft angle of 145°. Our series focused on the localization of the so-called contact spot on the bone bed formed to fix the acetabular component of the hemispherical endoprosthesis, and distribution of equivalent stresses and contact pressure inside it. The simulation results showed that the distribution of the characteristics of the stress and strain of the bone and the acetabular component occurred in irregular and eccentric manner. Localization of the contact patch and distribution of equivalent stresses and contact pressure were close to optimal values that were typical for implants with stems having neck-shaft angles of 125° and 135° (Fig. 4, 5). Localization of the contact patch at the boundary between the bone and the surface of the acetabular component and distribution of equivalent stresses and contact pressure appeared to be eccentric for endoprosthetic model with the femoral component with neck-shaft angle of 145° and were characterized by upward and anterior displacements concentrating along the edge cups (Fig. 6).

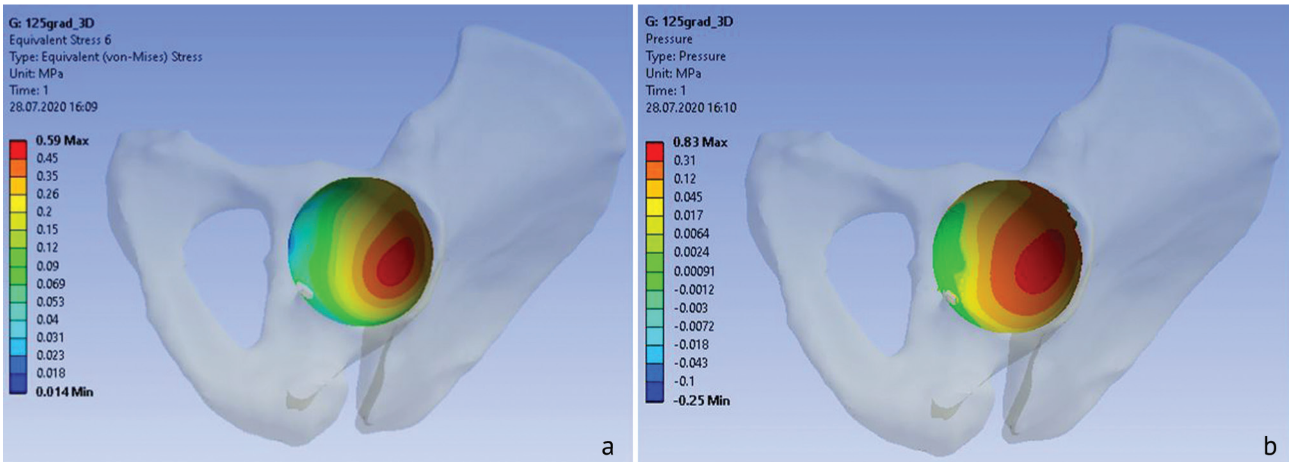

Fig. 4 Equivalent stresses (a) and contact pressure (b) on the contact surface of the acetabular component and the bone being characteristic of an artificial joint with 125° stem neck-shaft angle

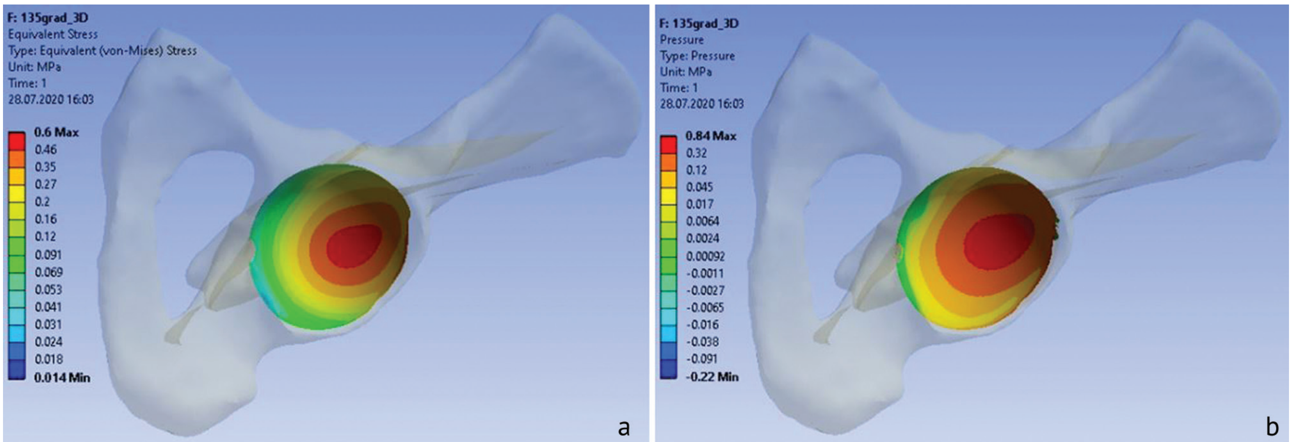

Fig. 5 Equivalent stresses (a) and contact pressure (b) on the contact surface of the acetabular component and the bone being characteristic of an artificial joint with 135° stem neck-shaft angle

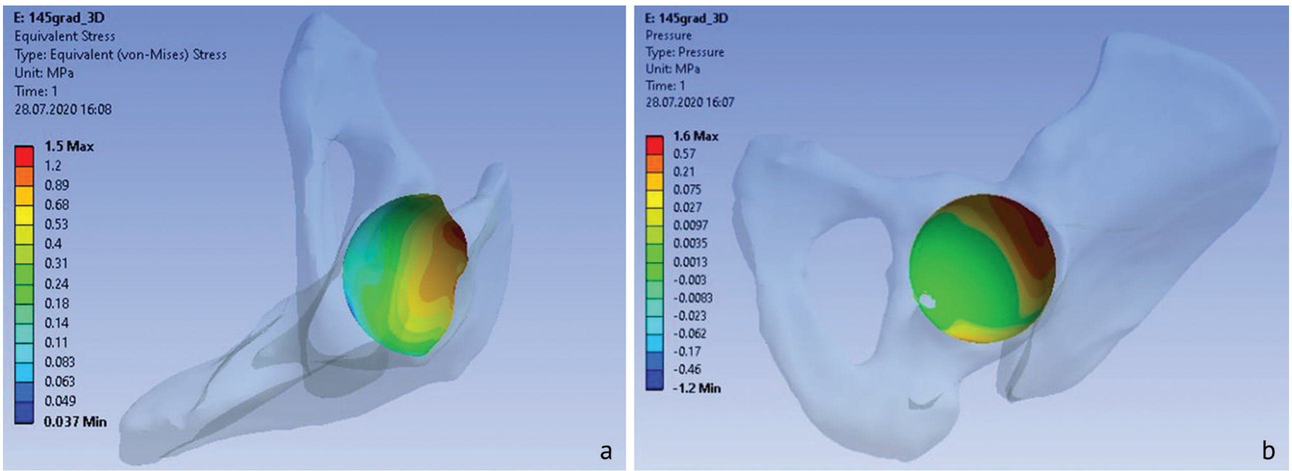

Fig. 6 Equivalent stresses (a) and contact pressure (b) on the contact surface of the acetabular component and the bone being characteristic of an artificial joint with 145° stem neck-shaft angle

DISCUSSION

Equivalent stresses that occur in the polyethylene liner and the contact pressure at the interface between the liner surface and the head of the artificial joint are significantly higher in case of cementless fixation of the femoral component with a neck-shaft angle of 145° as compared to stems with smaller neck-shaft angle. The data obtained are consistent with the results of biomechanical studies reported by L. Quagliarella et al. (2006). High values of the parameters in artificial joints with more varus stems could not be associated with polyethylene fatigue failure since the values were not consistent with the strength limits. A significant increase in equivalent stresses and contact pressure being characteristic of implants with the femoral component having a 145° neck-shaft angle, could become a prerequisite for the loss of stability in the bone-acetabular component system and lead to aseptic loosening.

The data obtained are fully consistent with the results of biomechanical studies of L. Quagliarella et al. (2006) [4]. The effect of NSA on the parameters of contact pressure is essential, since wear and debris-associated osteolysis decrease with a decrease in the neck-shaft angle. Researchers suggest that the use of stems with NSA equal to 125° is indicated in young patients with good bone quality, provided that the same length of the lower limbs is achieved [4]. Our series showed the eccentric localization of the contact spot at the border of the bone and the acetabular component and distribution of contact pressure and equivalent stresses within this spot as an even more important prerequisite for instability of the endoprosthetic cup that were typical for artificial joints with stems with a 145° NSA. The displacement of the contact patch upwards and forwards, as well as the concentration of stresses in the bone tissue along the edge of the cup were mechanical prerequisites for aseptic loosening. These data can complement the results of the study by L. Quagliarella et al. (2006) [4].

Comparison of the data that could substantiate more favorable conditions for implant functioning with smaller stem NSA, analysis of the implants survival confirmed the results of the biomechanical study performed. N. Edwards et al. (2017) analyzed the data of the Danish registry of hip arthroplasty and reported that the Symax stems with a NSA close to 128° demonstrated a mean 6.5-year survival rate in more than 97.5 % of cases [16]. Our analysis of data of the Australian registry of hip arthroplasty also showed a high survival rate of implants with femoral components and NSA ranging between 125° and 135°.

The proportion of revisions at 10 years due to aseptic instability was 2.7-3.8 % for implants with a MS 30 stem (NSA 124-135°) 2.4-4.1 % for Natural hip stem (NSA 130°), 3.8-9.9% for the Omnifit stem (NSA 127-132°); 3.2-4.6 % for the Secur-fit femoral component (NSA 127-132°); 3.4-8.9 % for the Summit stem (NSA 130°); 2.9-3.9 % for the Synergy stem (NSA 131°) and 3.5-4.4 % for the Antology femoral component (NSA 131°), respectively [17].

CONCLUSION

The results of biomechanical modeling indicate that the value of the cervical-shaft angle of the femoral component of the implant may be one of the biomechanical prerequisites for aseptic loosening of the acetabular component of the cementless THA. The contact patch at the cup – bone border can shift upward and forward with an uneven distribution of equivalent stresses and contact pressure along the periphery of the acetabular component with use of wedge-shaped stems and a 145° NSA. Implants with stems having NSAs of 125° and 135° are characterized by a well-centered contact spot and a uniform distribution of the stress and strain parameters. However, the experimental biomechanical study presented has a number of limitations. The latter are associated with load being modeled in a static vertical position only with support on both lower limbs with no consideration to muscle contraction, displacement of the center of gravity of the body and the position of the implant components at the gait. Comparison of the findings with information from registers on THA survival does not take into account the possible influence of other factors [17].

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