Acta of Bioengineering and Biomechanics
Vol. 10, No. 4, 2008

Stress distribution around a TKR implant: are lab results consistent with observational studies?

DAMIAN KUSZ[1], PIOTR WOJCIECHOWSKI[1], ŁUKASZ S. CIELIŃSKI[1,*],
ALEKSANDER IWANIAK[2], JACEK JURKOJĆ[3], DAMIAN GĄSIOREK[3]

[1] Department of Orthopaedics and Traumatolgy, Medical University of Silesia, Katowice, Poland.
[2] Department of Materials Science, Silesian University of Technology, Katowice, Poland.
[3] Department of Applied Mechanics, Silesian University of Technology, Gliwice, Poland.

Malalignment of Total Knee Replacement prosthesis has been reported to limit the implant survival time. We hypothesized that this may be secondary to excessive stress occurring at the bone–implant interface, resulting from abnormal load transfer across the knee joint.

In this study, we conducted Finite Element Analysis of a geometrical model of the knee joint after Total Knee Replacement with different axial alignments. The calculated stresses and displacements were significantly higher with varus knee malalignment than with the valgus one. The stresses are not high enough to pose a serious risk of a crack or a fracture but might be responsible for chronic pain reported by some patients. In cases where optimal implant positioning is not possible, slight valgus malalignment might produce better results than varus.

Key words: *Total Knee Replacement, Finite Element Analysis, malalignment*

1. Introduction

Degenerative joint disease has become a major medical and social problem. It accounts for up to 60% of all chronic medical conditions affecting people aged over 60 years and is one of the most common causes of disability (secondary only to cardiovascular disorders) [1]–[3].

Advanced osteoarthritis (OA) of major load-bearing joints such as the knee results in substantial deterioration of functional ability and life quality. There are many treatment options for knee OA, but the only management that relieves pain and enables functional recovery and return to previous activities is Total Knee Replacement (TKR) surgery.

Unfortunately, a growing number of the TKR surgeries performed have been followed by an increased need for revision procedures, which underlines the need for the good understanding of mechanisms responsible for treatment failure, so that any of predisposing factors could be eliminated or controlled [4]–[8].

One of the most important modes of failure after TKR is implant loosening. There are reports indicating that knee misalignment during TKR procedure is associated with reduced implant survival: implantation within 4° of the correct mechanical axis yields 90% survival ratio in the 10-year period of follow-up, whereas in cases where misalignment exceeds 4°, the survival ratio is reduced to 70% [4], [7], [9]–[11].

The reason for the decreased implant survival has not been clearly elucidated. We assumed that excessive stress occurring at the bone–implant interface, resulting from abnormal load transfer across the knee joint, might be the factor responsible for treatment failure. In order to verify our hypothesis, we conducted Finite Element Analysis of the geometrical

---

* Corresponding author: Łukasz S. Cieliński, Department of Orthopaedics and Traumatolgy, Medical University of Silesia, ul. Ziołowa 45/47, 40-635 Katowice, Poland. E-mail: lukasc@mp.pl

Received: September 4th, 2008
Accepted for publication: December 3rd, 2008

model of the knee joint after TKR procedure with different axial alignments [5], [6], [12], [13].

The aim of this study was to determine the distribution of stresses and displacements within osseous elements of the knee joint after the implantation of total knee prosthesis in different axial alignments.

2. Material and methods

Due to ethical considerations, in vivo analysis of stresses and displacements within the knee joint after TKR procedure was not feasible. Therefore, we created a geometrical model of femur and tibia after implantation of knee prosthesis and performed computer Finite Element Analysis to calculate stresses and displacements.

2.1. Geometrical model for finite element analysis

A mathematical model of normal tibia and femur was downloaded from the University of Nevada server [14]. Both bones were divided into cortical and cancellous parts and shaped in a way that resembles surgical resection of bone ends (e.g., the articular surface of tibia was “removed” with a “cut” in a horizontal plane). Subsequently, a model of PFC ® Sigma™ total knee prosthesis, (DePuy Orthopaedics, Inc., Warsaw, IN, USA) obtained by 3D scanning of the actual prosthesis, was combined with the relevant bony structures using surface sharing technique. The model of tibia was merged with the model of a knee prosthesis, assuming that the implant plateau is supported by cortical bone and implant keel penetrates cortical bone.

In order to apply boundary conditions and perform calculations, the model was meshed with the use of tetrahedral, 10-node elements. The assumed characteristics of the model materials (Young modulus and Poisson’s ratio) were respectively: cortical (compact) bone: 16000 MPa, 0.28; cancellous bone: 60 MPa, 0.46; tibial implant (Ti6Al4V alloy): 108000 MPa, 0.30; femoral implant (CoCrMo alloy): 210000 MPa, 0.30 and polyethylene insert: 1300 MPa, 0.30. To shorten the time needed for calculations the model was limited to the prosthesis and the proximal end of tibia. The model was then fixed in space by assigning zero degrees of freedom to the inferior aspect of the proximal tibia (figure 1).

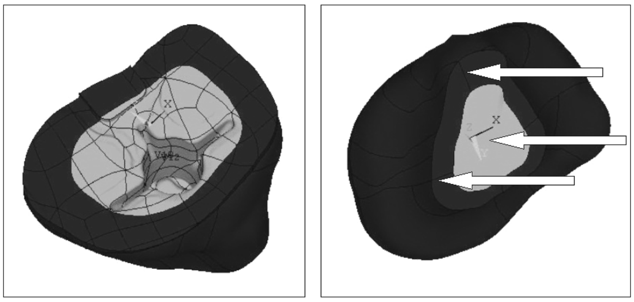

Fig. 1. Model of tibia, inferior aspect.
Arrows indicate surfaces with 0 degrees of freedom

2.2. Calculations

Calculations were performed with ANSYS™ software package (ANSYS Inc., Canonsburg, Pennsylvania, USA). Due to the high level of complication of our model, exceeding computational power of the available computer, calculations were performed separately for the femoral and tibial parts as well as for the polyethylene insert. The calculations for prosthetic insert were made for different assumed width to reflect polyethylene wear. In this paper, only the results pertaining the tibial part are given.

In order to simplify calculations, we disregarded the properties of bone cement (the cement mantle is thin and very hard, so it might be assumed that its influence on stress distribution within bone could be neglected). Loads acting at a knee endoprosthesis were divided into medial and lateral components applied at the points of contact with femoral part of the prosthesis. The load was simulated by concentrated forces applied at nodes. In the calculations, we assumed a net force of 4000 N, which was found to be the maximum load transferred across the knee joint during stance phase (single limb support) of gait in a person with body mass of 85 kilograms [15].

The calculations were performed for equal loading of the medial and lateral knee compartments (as in cases of anatomical knee alignment) and unequal loading (as with valgus or varus malalignment). Component forces were applied at 20 selected nodes, representing the area of contact with femoral part of the knee prosthesis. The values of component forces were determined by dividing the value of net forces acting, respectively, at the medial or lateral knee compartment by the number of the nodes (twenty) at which the forces were applied. The calculated values of net forces are given in table 1. We performed calculations for knee alignment ranging from 3° of valgus to 3° of varus, because such an alignment of endoprosthesis is most common following TKR surgery.

Table 1. Assumed distribution of forces acting across joint surfaces

Alignment	Force applied on medial part of endoprosthesis (N)	Force applied on medial part of endoprosthesis (N)
3° of varus	2870	1130
2° of varus	2580	1420
1° of varus	2300	1700
Correct (neutral) position	2000	2000
1° of valgus	1700	2300
2° of valgus	1420	2580
3° of valgus	1130	2870

3. Results

3.1. Normal knee alignment

For neutral alignment, we assumed an equal loading of the medial and lateral knee compartments. The maximum values of stresses, displacements and strain were calculated and are, respectively, as follows: implant: 104.93 MPa, 0.09 mm, 0.001; cortical bone: 59.43 MPa, 0.083 mm, 0.0037; cancellous bone: 1.04 MPa, 0.084 mm, 0.017. Maps of stress distribution are shown in figure 2. It should be kept in mind that the maximum stress would appear at the nodes, where force was applied.

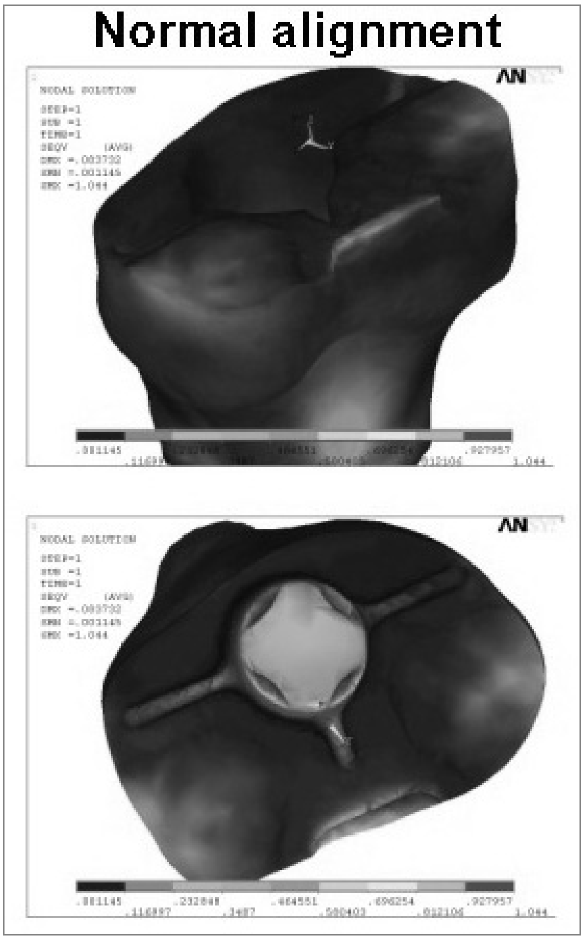

Fig. 2. Maps of stress distribution within tibia (normal alignment)

The results calculated for bone should be most carefully analyzed, as the pathologic changes within bone may lead to pain or even to implant loosening. In the cancellous bone, the maximum reduced stresses (calculated according to Huber and von Misses theory) occur at the interface between bone and implant keel. In the cortical bone, the maximum stress occurs at the bone–implant interface, as well as at the junction between a tibial condyle and shaft. Distribution of displacements follows the same pattern – the greatest net displacements occur in the medial condyle area. It is noteworthy that despite equal loading of both compartments, the distribution of stresses and displacements is not uniform.

3.2. Varus knee alignment

With varus alignment, there is an increased load across the medial knee compartment. The calculations of stresses, displacements and strain were performed for 1°, 2° and 3° of varus alignment, and their maximum values are given in table 2. Maps of stress distribution are shown in figure 3. It should be kept in mind that the maximum stress would appear at the nodes, where force was applied.

Table 2. Maximum stresses, displacements and strain within implant and bone calculated for varus knee alignment

Knee alignment	Stress (MPa)	Displacement (mm)	Strain
1° of varus			
Implant	120.0	0.11	0.0012
Cortical bone	67.83	0.099	0.0042
Cancellous bone	1.11	0.099	0.018
2° of varus			
Implant	134.8	0.127	0.0013
Cortical bone	75.7	0.115	0.0047
Cancellous bone	1.17	0.113	0.019
3° of varus			
Implant	149.79	0.15	0.0015
Cortical bone	83.85	0.13	0.0052
Cancellous bone	1.23	0.13	0.02

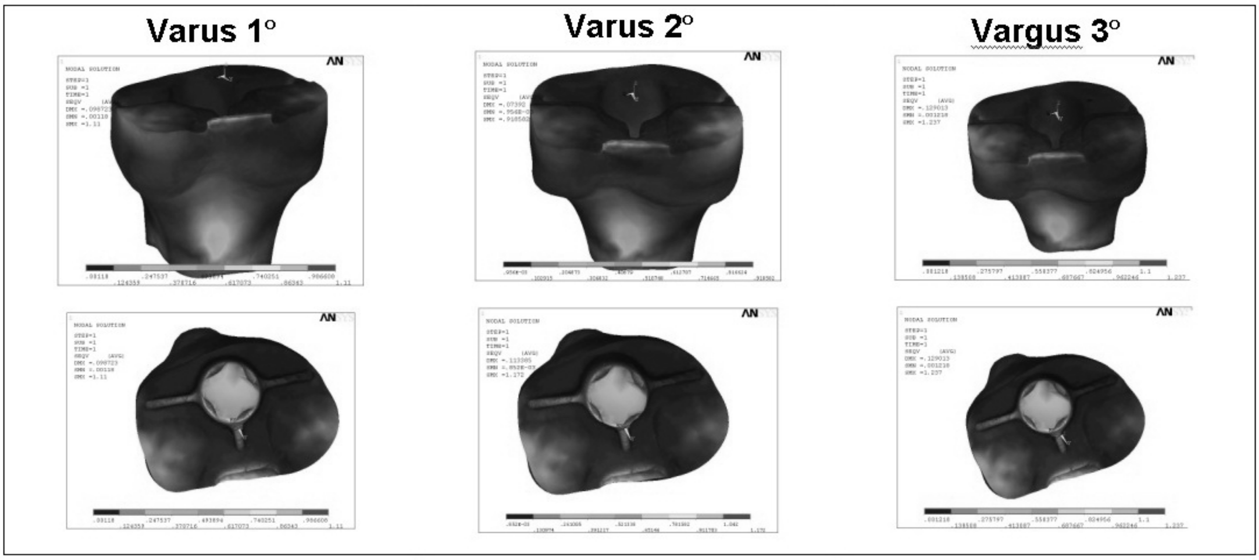

Fig. 3. Maps of stress distribution within tibia (varus alignment)

In the cancellous bone, the maximum reduced stresses (calculated according to Huber and von Mises theory) occur at the interface between bone and implant keel. Uneven joint loading resulting from varus misalignment is associated with accumulation of stresses at the medial tibial condyle. Likewise, in the cortical bone the stresses are greater at the bone–implant interface at the medial aspect of tibia. Stress accumulation (more pronounced at the medial side) occurs also at the shaft–condyle junction. The distribution of displacements follows the same pattern – the greatest net displacements occur in the medial condyle.

3.3. Valgus knee alignment

With valgus alignment, there is an increased load across the lateral knee compartment. The calculations of stresses, displacements and strain were performed for 1°, 2° and 3° of valgus alignment, and their maximum values are given in table 3. Maps of stress distribution are shown in figure 4. It should be kept in mind that the maximum stress would appear at the nodes, where force was applied.

In the cancellous bone, the maximum reduced stresses (calculated according to Huber and von

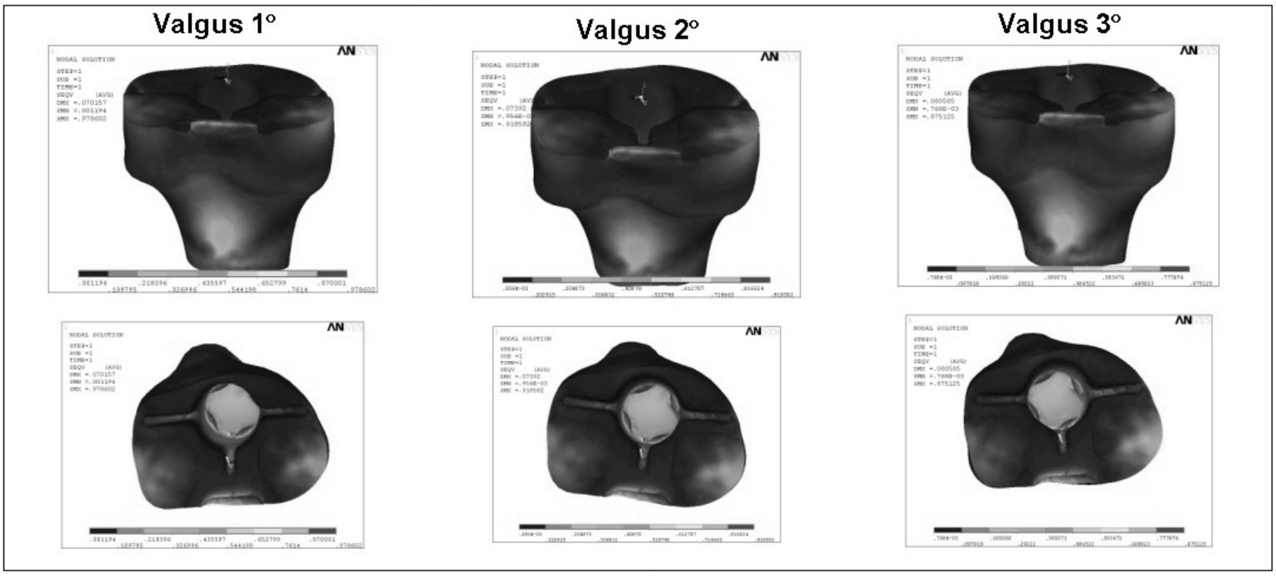

Fig. 4. Maps of stress distribution within tibia (valgus alignment)

Misses theory) occur at the interface between bone and implant keel. Uneven joint loading resulting from valgus misalignment is associated with an accumulation of stresses in the lateral tibial condyle. Likewise, in the cortical bone the stresses are greater at the bone–implant interface at the lateral aspect of tibia. Stress accumulation (more pronounced at the lateral side) occurs also at the shaft–condyle junction. The distribution of displacements follows the same pattern – the greatest net displacements occur in the lateral condyle.

Table 3. Maximum stresses, displacements and strain within implant and bone calculated for valgus knee alignment

Knee alignment	Stress (MPa)	Displacement (mm)	Strain
1° of valgus			
Implant	119.7	0.074	0.0014
Cortical bone	54.8	0.068	0.0034
Cancellous bone	0.979	0.07	0.016
2° of valgus			
Implant	134.3	0.075	0.0016
Cortical bone	61.6	0.067	0.0038
Cancellous bone	0.92	0.074	0.015
3° of valgus			
Implant	149.5	0.082	0.0018
Cortical bone	68.5	0.074	0.0043
Cancellous bone	0.875	0.08	0.0146

4. Discussion

Due to increasing life expectancy, knee osteoarthritis is becoming both medical and social problem. The costs associated with treatment of this condition might be decreased by improving survival time of TKR implants.

Correct implant alignment and restoration of normal limb axis are major factors enhancing the TKR survival. There are reports that link increased implant loosening with failure to restore correct limb axis [6], [7], [10], [16]. The results of our study show that the stresses generated both in implant and bone are not high enough to pose a risk of inducing a crack or a fracture. However, one should carefully analyze the results calculated for bone, as the pathologic changes within bone may lead to pain or even to implant loosening [4], [6], [7].

The analysis of our results strongly suggests that the varus implant malalignment is much worse than the valgus malalignment. The values of stresses, displacements and strain within medial compartment of a knee in varus position are much higher than the respective values within lateral compartment of a knee in valgus position. Therefore, in our view, surgical resection of the medial tibial condyle during TKR surgery should be as conservative as possible or even the condyle should be reconstructed with grafts. When the height of the medial tibial condyle is restored, it facilitates correction of limb axis [17]. We also suggest that in cases where one cannot achieve optimal implant positioning, implantation of knee prosthesis in valgus is preferable to varus alignment. The stress accumulation at the junction between shaft and tibial condyles is not significant enough to pose a risk of a fracture; however, it might be responsible for persistent pain at this site, reported by some patients [4], [6], [7], [18].

Most of the patients undergoing TKR are women over 60 years of age. In that population, obesity and osteoporosis are quite frequent. Obesity is one of the risk factors predisposing for knee OA, but it is not the sole cause responsible for development of this condition [19]. Nevertheless, it might increase loading of the tibial condyles in a malaligned artificial knee joint [4], [7]. Fortunately, in this age group the females with mild obesity may expect more than 10 years of implant survival [20].

There are contradictory reports on whether obese patients have worse outcomes of treatment for OA with TKR. It is believed that neither clinical and radiological outcomes of TKR nor the incidence of aseptic implant loosening are affected by mild obesity [21]–[23]. On the other hand, it is associated with patellofemoral complaints, decreased joint range of movements and increased incidence of contralateral knee replacement [10], [19]. An increased body weight has a detrimental effect on the survival of polyethylene liner. Especially, obesity with knee misalignment (when limb axis was not adequately corrected during the surgery) leads to rapid and asymmetrical polyethylene wear [5], [8], [18], [22]–[24]. Therefore, indications for Total Knee Replacement have to be considered very carefully in obese patients.

5. Conclusions

1. The stresses calculated in both implant and bone are not high enough to pose a serious risk of a crack or a fracture.

2. Varus knee malalignment results in higher values of stresses and displacements than the valgus one. Therefore, when a correct implant positioning during surgery is not possible it might be better to choose a slight valgus malalignment than the varus one.

3. Stresses are accumulated at the diaphyseal–metaphyseal junction. The cumulated values are not very high, but might be responsible for chronic pain reported by some patients after TKR surgery.

Acknowledgements

The study was conducted in compliance with the current laws of the country in which it was performed and the appropriate approval from institutional review board was granted. Some of the authors received financial support from the State Committee for Scientific Research (research grant No. 3 T08C 029 27) in years 2004–2007.

References

[1] Hulet C., Sabatier J.P., Souquet D., Locker B., Marcelli C., Vielpeau C., *Distribution of bone mineral density at the proximal tibia in knee osteoarthritis*, Calcif. Tissue Int., 2002, 71(4), 315–322.

[2] Terauchi M., Shirakura K., Katayama M., Higuchi H., Takagishi K., *The influence of osteoporosis on varus osteoarthritis of the knee*, J. Bone Joint Surg. Br., 1998, 80-B, 432–436.

[3] Wojciechowski P., Kusz D., Iwaniak A., Cieliński Ł., *Analiza wyników całkowitych endoprotezoplastyk stawu kolanowego operowanych w Katedrze i Klinice Ortopedii i Traumatologii Narządu Ruchu Śląskiej Akademii Medycznej w Katowicach*, Chir. Kolana Artroskopia Traumatol Sport, 2006, 3(3), 19–26.

[4] Au A.G., Liggins A.B., Raso V.J., Amirfazli A., *A parametric analysis of fixation post shape in tibial knee prostheses*, Med. Eng. Phys., 2005, 27(2), 123–34.

[5] Knight L.A., Pal S., Coleman J.C., Bronson F., Haider H., Levine D.L., Taylor M., Rullkoetter P.J., *Comparison of long-term numerical and experimental total knee replacement wear during simulated gait loading*, J. Biomech., 2007, 40(7), 1550–1558.

[6] Laz P.J., Pal S., Halloran J.P., Petrella A.J., Rullkoetter P.J., *Probabilistic finite element prediction of knee wear simulator mechanics*, J. Biomech., 2006, 39(12), 2303–2310.

[7] Perillo-Marcone A., Taylor M., *Effect of varus/valgus malalignment on bone strains in the proximal tibia after TKR: an explicit finite element study*, J. Biomech. Eng., 2007, 129(1), 1–11.

[8] Yuan X., Ryd L., Huiskes R., *Wear particle diffusion and tissue differentiation in TKA implant fibrous interfaces*, J. Biomech., 2000, 33(10), 1279–1286.

[9] Fukupoka S., Yosida K., Yamano Y., *Estimation of the migration of tibial components in total knee arthroplasty, a roentgen stereophotogrammers analysis*, J. Bone Joint Surg. Br., 2000, 82-B, 222–227.

[10] Moon M.S., Kim J.M., Woo Y.K., *Restoration of knee motion after total knee arthroplasty: subvastus approach and alternate flexion and extension splintage*, Ryumachi, 1997, 37, 146.

[11] Soininvaara T.A., Jurvelin J.S., Miettinen H.J., Suomalainen O.T., Alhava E.M., Kroger P.J., *Effect of alendronate on periprosthetic bone loss after total knee arthroplasty: a one-year, randomized, controlled trial of 19 patients*, Calcif. Tissue Int., 2002, 71(6), 472–477.

[12] Halloran J.P., Petrella A.J., Rullkoetter P.J., *Explicit finite element modeling of total knee replacement mechanics*, J. Biomech., 2005, 38(2), 323–31.

[13] Halloran J.P., Easley S.K., Petrella A.J., Rullkoetter P.J., *Comparison of deformable and elastic foundation finite element simulations for predicting knee replacement mechanics*, J. Biomech. Eng., 2005, 127(5), 813–818.

[14] http://www.cineca.it/hosted/LTM-IOR/back2net/ISB_mesh/mesh_list.html (retrieved on 20.06.2006).

[15] Tejszerska D., Jurkojć J., Michnik R., *Modelling of human knee during gait*, Machine Dynamics Problem, 2004, 28(4), 153–158.

[16] Bindelglass D.F., Vince K.G., *Patellar tilt and subluxation following subvastus and parapatellar approach in total knee arthroplasty: implication for surgical technique*, J. Arthroplasty, 1996, 11, 507–511.

[17] Whiteside L.A., *Correction of ligament and bone defects in total arthroplasty of the severely valgus knee*, Clin. Orthop., 1993, 288, 234–45.

[18] Ketata H., Krichen A., Kharrat M., Dammak M., *Mechanical response of polyethylene tibial component using compression loading contact test: experimental and finite element analysis*, Technol. Health Care, 2006, 14(6), 479–487.

[19] Dziewulski M., *Choroba zwyrodnieniowa stawów kolanowych – leczenie przy zastosowaniu dostawowej suplementacji hialuronianem nowej generacji* (część 2), Polish Journal of Sports Medicine, 2003, 19(2), 117–121.

[20] Marcacci M., Iacono F., Zaffagnini S., Visani A., Loreti I., Petitto A., Neri M.P., *Total knee arthroplasty without patellar resurfacing in active and overweight patients*, Knee Surg. Sports Traumatol. Arthrosc., 1997, 5(4), 258–261.

[21] Griffin F.M., Scuderi G.R., Insall J.N., Colizza W., *Total knee arthroplasty in patients who were obese with 10 years follow-up*, Clin. Orthop., 1998, 356, 28–33.

[22] Hamoui N., Kantor S., Vince K., Crookes P.F., *Long-term outcome of total knee replacement: does obesity matter?* Obes. Surg., 2006, 16(1), 35–38.

[23] Heck D.A., Clingman J.K., Kettelkamp D.G., *Gross polyethylene failure in total knee arthroplasty*, Orthopedics, 1992, 15(1), 23–28.

[24] Wimmer M.A., Andriacchi T.P., *Tractive forces during rolling motion of the knee: implications for wear in total knee replacement*, J. Biomech., 1997, 30(2), 131–137.