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Biomedicine

Computer Simulations of Strain-Deformed Conditions in Knee Prosthesis Components if Tibial Condyles have Defects

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Relevance: Gonarthrosis (knee arthrosis) gets registered in 50.6-54.5% of cases in patients suffering from dystrophic diseases of their lower extremities' joints. In 86%, it affects people of workable age, leading to disability in 6.5-14.6% cases. Given this, gonarthrosis is a relevant medico-social problem. Surgical methods (bone plastics, metal insertion, others) for bone defects while knee arthroplasty (KA) are still underdetermined. Study methods: At the facilities of the Laboratory of Biomechanics at the SI "The Institute of Traumatology and Orthopedics, NAMS of Ukraine" and on the grounds of a digital model elaborated, we studied strain-deformed conditions in components of a knee prosthesis in the case of limb varus deformity within knee arthroplasty using a regular and extended stem, bone defect replaced with bone autografts 5 mm and 10 mm, respectively. Results: We have discovered that while knee arthroplasty upon conditions of a varus deformity with a medial tibial condyle's defect, it is possible to fill the defect with an autograft bone insert up to 5 mm high with the use of a regular (short) tibial prosthesis stem. If the defect's size falls within 5 mm and 13.5 mm, it is biomechanically grounded to use a prosthetic nail combined with an extensor. Bone defects over 13.5 mm require replacement with massive metal insertions. Practical importance: the research enables us to establish a differentiated approach to eliminate different tibial condyles defects while doing knee arthroplasties. Conclusion: Implementation of this study's findings shall improve the efficiency of medical aid provided to overcome this severe disease. *© 2022 Bull. Georg. Natl. Acad. Sci.*

Knee, tibial defects, arthroplasty, regular and extended prosthesis stem, biomechanical study

Total knee arthroplasty (TKA) is the method of choice in the late stages of knee osteoarthritis. The development of knee osteoarthritis usually relates to a moderate or severe varus deformity with a bone defect of medial condyles. It causes implants deficiency and later demand for revision arthroplasty. The available options to eliminate bone defects include a massive tibial resection, bone cement to fill the defect with or without screw augmentation, bone plastics by autograft or

allograft, metal augments, metaphyseal cones. However, despite many operations made, the criteria of choice (bone plastics, metal insertions, extended tibial nail) for knee arthroplasty within an implant site's defect are still underdetermined.

That's why we saw it scientifically interesting to carry out a computer simulation of strains related to a tibial extensor used with knee prostheses depending on a tibial condyle's defect.

Objectives: to substantiate a differentiated approach to the surgical treatment of knee osteoarthritis, relying on the analysis of mathematically simulated strains within a bone-endoprosthesis system with different defects of tibial condyles.

Materials and Methods

To calculate the strain-deformed conditions of a modeled knee joint with an implanted knee endoprosthesis, we made a profit of the facilities of the Laboratory of Biomechanics at SI "The Institute of Traumatology and Orthopedics of Ukraine" attested by SE "Ukrmetrteststandard" (Certificate PT-72/15 of 12.03.15). To solve this challenge, we split it into stages. The first task was to model a knee joint with a prosthesis, its elements of different mechanical features. The simulation relies upon anatomical and anthropometric data of patients, so it is realistic to the maximum possible extent.

For further calculations of the strain-deformed conditions (SDC), we involved the ANSYS software package with its finite element model. The computations considered physical features of bone and cartilage, taken from literature sources [1, 2].

The constructed 3D mathematical model came to the ANSYS environment for further calculations. For metal elements, the maximum strength taken was 586 MPa, for a polyethylene insert – 113 MPa. Inasmuch cortical surfaces of femoral and tibial bones get removed during an arthroplasty, we took the maximum strength of the bone tissue as under 3.5 MPa in its compact layer and up to 25 MPa in its cancellous one. The strains exceeding these values destroy the model's elements. In a semi-automatic mode, we generated a finite-element model comprising 478,303 nods and 286,093 elements, enough to ensure the required accuracy of calculations. The accepted conditions were as follows: - along with the plane (a) – rigid fixation; - along the plane (b) – 700N load on the model, corresponding to 70 kg of human body weight.

In the next stage, we followed strain-deformed conditions of the models upon the limb's varus deformity using a regular stem and a stem with a tibial extensor to replace a bone tissue defect with an autograft 5 and 10 mm high.

Results and Discussion

Analysis of maximum strains in the tibial plateau of different knee prosthesis models, depending on the size of bone autograft insert has demonstrated that if the insert's size exceeds 7.3 mm, the SDC values in a model with a regular stem exceed the maximum strength of cancellous bone tissue (Fig). In clinical

Table. Values of the measured maximum strain in the knee joint model's tibial plateau for standard arthroplasty and the same in varus deformity of an extremity with bone defect of a tibial condyle

The model's elements	Maximum strain in the model of a knee joint (*MPa)*			
	Regular arthroplasty	Arthroplasty in varus deformity and bone defect		
		5 mm	10 mm	13.95 mm
Standard prosthetic stem	1.85	2.79	4.23	–
Stem with a tibial extensor	1.06	1.92	2.81	3.50

conditions, it might destroy tibial plateau edges in this area. In the presence of a 10 mm bone autograft, the strains in the contact area between the tibial plateau and a regular tibial prosthetic component exceed the maximum allowed ones by 20% – 4.23 MPa (Table). However, with a tibial extensor applied, the maximum strain appears when the autograft's size reaches 13.95 mm.

Analysis of the computer simulation has demonstrated that during a regular TKA upon a varus deformity with a medial tibial condyle defect, the said defect may be filled in with an autologous bone graft up to 5 mm high using a regular (short) tibial prosthetic stem. In these conditions, the stability of a "bone-prosthesis" biomechanic system is achievable (the values of strains on the tibial plateau equal 2.79 MPa).

The increase in the autograft's height to over 5 mm in combination with a short tibial prosthetic stem raises the SDC values in all the elements of the simulated knee to those exceeding the maximum allowed strength (4.23 MPa). It may destroy the plateau's cancellous bone around the tibial prosthetic component.

A tibial extensor applied for a tibial medial condyle's defect over 5 mm combined with a varus deformity of a knee unloads significantly the "bone-prosthesis" biomechanical structure thanks to redistribution of the load on the tibial prosthetic component (with a 10 mm insert, the tibial plateau strain makes 2.81 MPa).

In a case of a condylar defect repair with an autograft bone combined with a tibial extensor, the biomechanical system remains stable with an insert up to 13.95 mm high. If a defect is larger, metal inserts (augments) may help achieve the required stability.

Discussion: International literature sources are actively discussing the matter of bone plastics during total knee arthroplasty. Hosaka K. et al. are sure that a bone autograft applied during knee arthroplasty surgery is a relatively easy and efficient procedure to ensure good bone union [3]. Sugita T. et al. got promising results after the morselised bone graft to fill in the defects in the medial tibia. The authors recommend this method for defects ≥ 3 mm deep [4]. Tanwar Y.S., Kharbanda Y. carried out a retrospective analysis

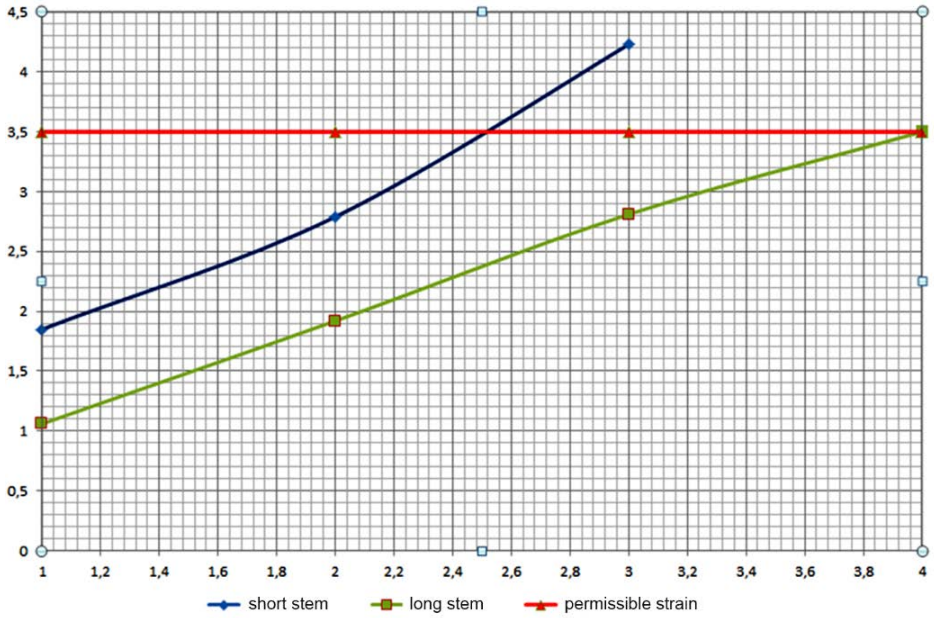

Fig. Results of maximum strains in a tibial plateau for long and short stems depending on the size of autologous bone insert.

and observed patients with a severe (over 20 degrees) varus deformity who underwent a primary knee arthroplasty with impaction bone plastics. The authors claim that the impaction-bone plastic as a remedy for bone defects remains underestimated by orthopedic surgeons, especially for the primary knee arthroplasty, as it recovers the bone tissue [5, 6]. Sohn J.M. et al. highlighted the high efficiency of the impaction bone autograft to fill medial tibial plateau defects during the initial knee arthroplasty within not less than seven years. It is economically expedient, moreover, promotes bone tissue preservation for following operations. Structural implants should be applied if a defect is <5 mm deep and covers 25-40% of the proximal tibial section. For bigger peripheral vertical defects, impaction bone plastics on a net should be preferred [7]. According to the results of a tibial bone graft study upon a press-fit total knee arthroplasty using a finite element method, Totoribe K., in his research substantiates the refusal from large soft bone grafts in favor of rigid bone grafts to reduce micromotions and mechanic load in the adjacent bone [8]. According to Aggarwal A.K. et al., bone defects smaller than 10 mm could get filled with bone cement alone (< 5–6 mm) or combined with screws (6-10 mm). In young, active patients, defects within 10-25 mm should be treated with structural bone grafts (auto- or allografts), while in older ones and less demanding – with metal blocks. To fill the defects > 25 mm, they propose an impaction bone graft and a metal net, or in the case of senior patients – with porous tantalum cones used jointly with SSK implants, stem extensors, and an active insert [9]. Based on a retrospective analysis, Park M.H. et al. concluded that the use of a short extending stem for a tibial component while an initial total knee arthroplasty in patients with a severe varus deformity exceeding 8 degrees may decrease the share of tibial component loosening and increase the service life of the implant [10]. In our research, this opinion has found its biomechanical grounding. Moreover, we demonstrated the expediency of a regular prosthetic stem and bone plastics for tibial condylar defects up to 5 mm and noted the use of a tibial extensor for bone defects larger in size.

Our results facilitate us to establish a differentiated approach, and in the future – to elaborate an algorithm of different tibial condylar defects while total knee arthroplasty and improve the efficiency of this severe disorder treatment.

Conclusion

With this study, we substantiated a differentiated approach to the planning of surgical intervention for the treatment of knee osteoarthritis with tibial condylar defects. It shall ensure higher efficiency of surgical treatment to this severe disorder.

ბიომედიცინა

მუხლის პროთეზის კომპონენტებში დეფორმირებული მდგომარეობის კომპიუტერული მოდელირება, ტიბიალური კონდილების დეფექტების შემთხვევაში

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**უკრაინის მედიცინის მეცნიერებათა ეროვნული აკადემია, ტრავმატოლოგიისა და ორთოპედიის ინსტიტუტი, კიევი, უკრაინა*
***ჟიტომირის ჰერბაჩევსკის სახ. რეგიონალური კლინიკური საავადმყოფო, ჟიტომირი, უკრაინა*

(წარმოდგენილია აკადემიის წევრის რ. ხეცურიანის მიერ)

გონართროზი (მუხლის სახსრის ართროზი) აღინიშნება ქვედა კიდურების სახსრების დისტროფიული დაავადებების მქონე პაციენტთა 50,6-54,5%-ში. ამ დაავადების მქონე ადამიანთა 86% შრომისუნარიანია. გონართროზი იწვევს ინვალიდობას 6,5-14,6%-ში. აქედან გამომდინარე, ეს დაავადება წარმოადგენს სამედიცინო-სოციალურ პრობლემას. უკრაინის მედიცინის მეცნიერებათა ეროვნული აკადემიის ტრავმატოლოგიისა და ორთოპედიის ინსტიტუტის ბიომექანიკის ლაბორატორიაში, შემუშავებული ციფრული მოდელის საფუძველზე, ჩვენ შევისწავლეთ მუხლის პროთეზის კომპონენტებში დეფორმირებული მდგომარეობა, მუხლის ართროპლასტიკაში კიდურის ვარუსული (varus) დეფორმაციის შემთხვევაში, ჩვეულებრივი და დაგრძელებული ღეროს გამოყენებით, ძვლის დეფექტის ჩანაცვლება ძვლის 5 მმ და 10 მმ აუტოტრანსპლანტატებით, შესაბამისად. ჩვენ აღმოვაჩინეთ, რომ მუხლის ართროპლასტიკის დროს ვარუსული დეფორმაციისას, მედიალური დიდი წვივის (ტიბიალური) კონდილის დეფექტით, შესაძლებელია დეფექტის შევსება 5 მმ-მდე სიმაღლის აუტოტრანსპლანტატი ძვლის ჩანართით ჩვეულებრივი (მოკლე) ტიბიალური პროთეზის ღეროს გამოყენებით. თუ დეფექტის ზომა ჯდება 5 მმ და 13,5 მმ ფარგლებში, ბიომექანიკურად დასაბუთებულია პროთეზის ფრჩხილის გამოყენება ექსტენზორთან (გამშლელი კუნთი) ერთად. 13,5 მმ-ზე მეტი ზომის ძვლის დეფექტები საჭიროებს ჩანაცვლებას მასიური ლითონის ჩანართებით. კვლევა საშუალებას გვაძლევს დავადგინოთ დიფერენცირებული მიდგომა მუხლის ართროპლასტიკის დროს ტიბიალური კონდილების სხვადასხვა დეფექტის აღმოსაფხვრელად. აღნიშნული კვლევის შედეგების განხორციელება გააუმჯობესებს სამედიცინო დახმარების ეფექტურობას ამ მძიმე დაავადების დასაძლევად.

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