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Biomechanics of the proximal interphalangeal joint after total joint replacement

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Abstract

Introduction Small joints arthroplasty of the hand including the proximal interphalangeal joint (PIPJ) is associated with the need to create anatomically adapted structures using optimal materials. Introduction of a new medical device requires comprehensive preclinical testing. **The objective** was to determine a range of loads allowed for the proximal interphalangeal joint after arthroplasty through analyzing the biomechanics to prevent critical conditions and complications. **Methods** A full-ceramic non-constrained anatomically adapted proximal interphalangeal joint implant was developed between 2016 and 2021 using an integrated approach with preclinical trials and a clinical study of 42 patients (25 males, 17 females) with PIPJ arthritis. A digital endoprosthesis was created with 3D-modelling. Critical conditions for the digital model imitating typical joint movements were explored with the use of finite element method and the findings to be employed in clinical practice. **Results** A stable biomechanical construct was intact with loads of 5 kilograms and a motion ranging from 0 to 60 degrees, with loads of 20 kilograms and a motion ranging between 0 and 30 degrees. Cortical bone could sustain loads up to 20 kilograms with a motion ranging between 0 and 60 degrees. Discussion Load capacity of the implant was explored considering the strength of bone tissue and zirconium ceramics as a material. The study set a vector for the development of the optimal mode of motor activity early after surgery and indicated the optimal range of motion to be applied after PIPJ arthroplasty. **Conclusion** The load up to 5 kg was optimal for the patient to be applied early after surgery with the range of flexion measuring less that 90°. The patient could use a load of 5 to 20 kg with flexion in the proximal interphalangeal joint measuring less than 30°. Endoprosthetic components were likely to get dislocated with a load of 20 kg and flexion angle of greater than 30°. Periprosthetic fracture could occur with flexion angle of greater than 60°.

Keywords: proximal interphalangeal joint replacement, finite element method, joints arthroplasty of the hand, digital modelling

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INTRODUCTION

Diseases and injuries of the proximal interphalangeal joint (PIPJ) including osteoarthritis of PIPJ occur in approximately 15.5 % of the population. Osteoarthritis of PIPJ is a degenerative disease that leads to a severe decrease in the quality of life, disability in various groups of population including those who are able to work in unavailability of adequate treatment [1, 2]. Arthrodesis in a functional position has long been the “gold standard” in the treatment of osteoarthritis of PIPJ providing reliable relief of pain and swelling, but the procedure is associated with restricted hand function [3]. Endoprosthetic replacement of PIPJ today is becoming the most preferred and promising solution for restoring the joint and the hand function. The procedure has evolved through a long evolution, starting from the 20s of the last century and now PIPJ implants are presented in the form of constrained (silicone) and non-constrained constructs made of metal-polyethylene and pyrocarbon [4, 5].

Despite the diversity of products all implants have their own advantages and disadvantages affecting the inconsistent functional results of PIPJ arthroplasty [6]. In recent years, zirconium ceramics have attracted the attention of clinicians and medical reseachers. Major qualities of the material including wear resistance, biocompatibility and biointertness, corrosion resistance are perfectly employed in orthopedic and dental implantology. In the last decade, the first reports on the use of all-ceramic endoprostheses were published in the world scientific literature attracting the attention of hand surgeons [7, 8, 9]. World practice has been developing into personalized medicine, and endoprosthesis of small joints of the hand suggests an optimal design of anatomically adapted implants and the ideal material for the manufacture [10, 11].

Scientific and technological progress in medicine is characterized by new medical products entering the market, pharmacological drugs, treatment methods and technologies. An innovation goes through the thorny path of preclinical testing before being used by a wide network of medical institutions; in relation to various types of implants, these are toxicological studies on cell cultures, technical testing of samples in a laboratory certified in a specific field, preclinical testing on laboratory animals and cadaver material [12].

Numerous reports on the severity of revision interventions during hand joint replacement initiated this digital study in order to protect the patient from additional physical and psycho-emotional injuries. Endoprosthesis of the PIPJ with non-constrained implants can be characterized by common complications including [13, 14]:

• dislocation in the implant;
• fracture of the stem;
• periprosthetic fracture of the phalanx.

The objective was to determine a range of loads allowed for the proximal interphalangeal joint after arthroplasty through analyzing the biomechanics to prevent critical conditions and complications.

MATERIAL AND METHODS

Forty-two patients with osteoarthritis of the PIPJ were examined by an orthopedic and trauma surgeon at the Samara State Medical University Hospital between 2016 and 2021. There were 25 male (59.5 %) and 17 female (40.5 %) patients with the mean age of 44 ± 2.71 years. The patients presented with pain, moderate swelling and severely limited movements in the PIPJ. The VAS scored 5 ± 1.4, and the average flexion in the PIPJ was 48.7 degrees. The patients underwent a comprehensive examination including collection of complaints and medical history, physical examination, radiography of the hand in two projections, and computed tomography (CT). 3D CT was performed for biomechanical examination of healthy and affected joints.

Dissection of 25 cadaveric hands was produced to explore the anatomy of the capsular-ligamentous apparatus of the PIPJ.

Based on the above research and analysis of the experience of foreign colleagues in the field of endoprosthesis of the PIPJ, the tendency to personalized medicine, we have developed the design of an all-ceramic unconstrained anatomically adapted endoprosthesis of the proximal interphalangeal joint (RF Patent for utility model No. 202476 dated 02/19/2021. Bull. No. 5) [15].

The product is a non-constrained endoprosthesis and is made of solid zirconium ceramics. The articular surfaces are made anatomically: the proximal component is represented by toroidal condyles and a groove between them, forming an arc of 210 degrees; the distal component has a concave surface, an ellipsoidal shape and a ridge antagonist of the groove in the middle. The design of the seating surfaces of the articular parts has two planes to ensure rotational stability with minimal resection of bone tissue. The stems have a conical shape and rounded at the tops for ease placement using the press-fit. The implant is presented in four sizes and supplied with a set of tools for placement. The endoprosthesis has undergone a full cycle of preclinical technical and toxicological tests: technical tests have been completed at the ANO Center for Quality, Efficiency and Safety of Medical Prescriptions, Moscow (Act No. 11/022.R-2021 dated November 10, 2021). Toxicological tests were performed in the physicochemical laboratory "Delma", Pushchino (program of toxicological studies of medical devices No. MI21-0208/02 dated August 2, 2021).

Medical science, which serves practical healthcare, involves the collective work of specialists of various specialties: doctors, design engineers, IT specialists, graphic designers. This effective tandem facilitates excellent results at the preclinical stage of research minimizing the risk of complications and other adverse events in clinical practice [16]. A database of CT scans in the DICOM format, 3D models generated with polygonal modeling, 3D sculpting, and automated modeling systems developed at the Institute of Innovative Development of SamSMU were used for the anatomical and biomechanical study of the PIPJ.

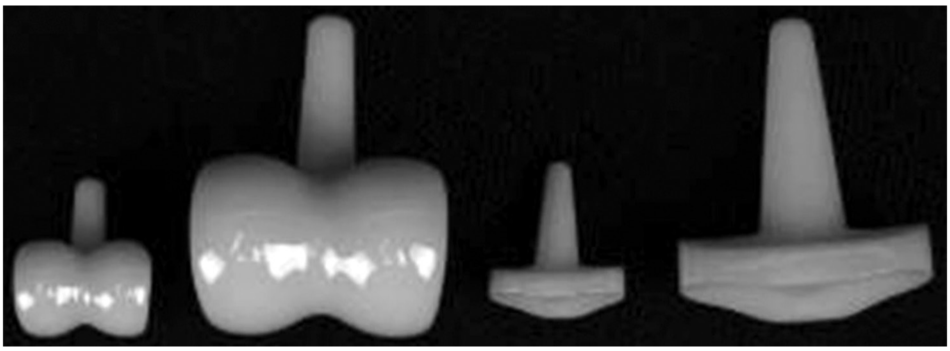

Fig. 1 All-ceramic, unconstrained, anatomically adapted proximal interphalangeal joint endoprosthesis, available in two sizes

ZBrush and Autodesk 3dsMax software systems were employed to obtain three-dimensional models of joints for a new endoprosthetic design. The finite element method was used for reproduction of critical conditions leading to complications. The finite element method (FEM) was the main method for analyzing the stress-strain conditions of the constructs, widely used in aircraft manufacturing, industry and construction. FEM is indispensable in the development of implants for orthopaedic use: it can be used to determine the effective loads on an endoprosthesis, a screw, plate, dental implant, etc. and on a musculoskeletal segment for prediction of the service life of the product at given loads and optimize the design at the preclinical stage. In this study, FEM was used in the Ansys software package [17, 18]. Major stereotypes were identified from a variety of hand movements and loaded as 3D models into the program. The ceramic properties presented in Table 1 were employed.

Table 1

Mechanical properties of ceramics

Property	Value
Density, g/cm^3	6
Average particle size, microns	< 1
Bending strength, MPa	900
Young's modulus, GPa	210
Vickers hardness, HV 0.1a	1200

Mechanical properties of cortical bone used to develop the digital model:

– Young's modulus 1.8×10^{10} Pa;

– tensile strength 146 MPa;

– specific gravity 1800 kg/m^3.

Cortical bone measurements were used for the digital model of PIPJ replacement using the Ansys software package, since modeling may suggest simplification and abstraction from the real scenario due to the complex reproduction of physiological and biomechanical processes in native bone. A solid model of the implant was integrated into the bone tissue, representing a biomechanical structure that was subjected to strength analysis. The purpose of the calculations was to analyze the stress of the construct, identify weaken areas in the bone and in the implant material to prevent destruction of the biomechanical components. Major stereotypes of movements were used to develop a digital finite element model which consisted of spherical gripping of objects with a flexion of 0, 30, 60 and 90 degrees in the PIPJ and compression of the object [19, 20]. The permissible working loads for joint flexion angles were determined based on the calculation of the stress condition of the biomechanical construct "implant – bone tissue".

Strength analysis was based on the finite element method. The biomechanical model was marked with Solid 45 finite elements with boundary conditions applied to the model: the bone tissue of the proximal phalanx was rigidly fixed along the surface of the end – the "rigid embedding" fastening, and forces were applied to the distal phalangeal element of the bone in the axial direction. The finite element model of the biomechanical construct is shown in Figures 2-5.

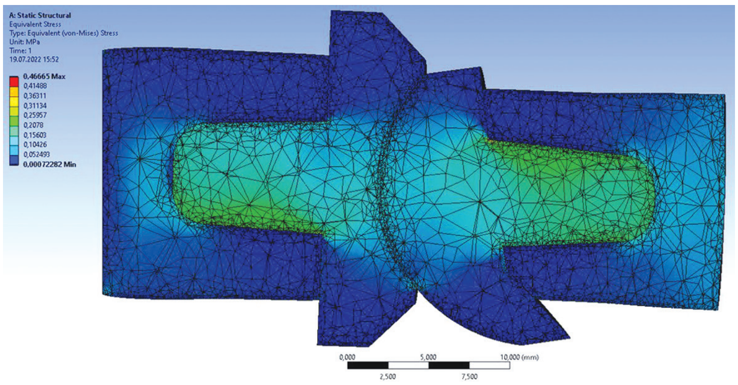

Fig. 2 Finite element model of an implanted PIP endoprosthesis. The model is shown with a load force of 1 kg with flexion of 0 in PIP 0º

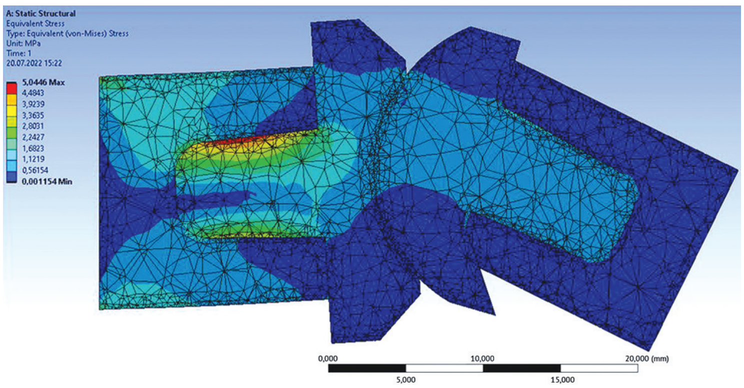

Fig. 3 Finite element model of an implanted PIP endoprosthesis. The model is shown with a load force of 5 kg. Flexion angle in PIP measuring 30º

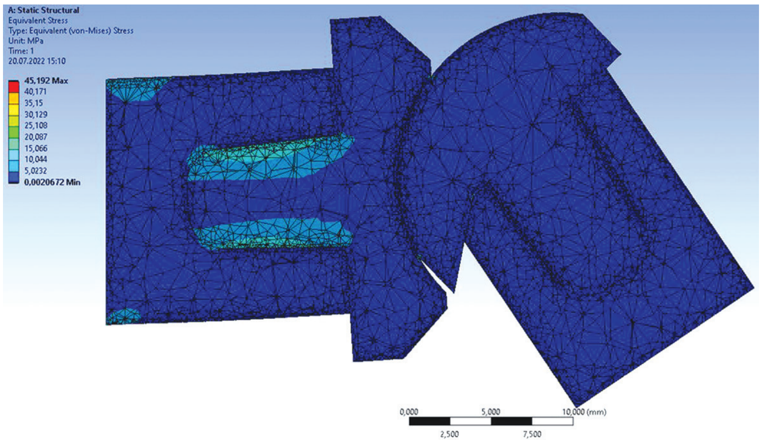

Fig. 4 Finite element model of an implanted PIP endoprosthesis. The model is shown with a load force of 10 kg. Flexion angle in PIP measuring 60º

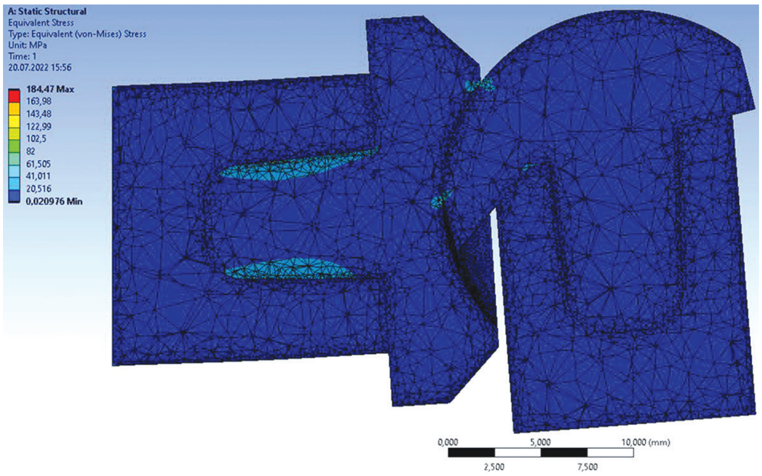

Fig. 5 Finite element model of an implanted PIP endoprosthesis. The model is shown with a load force of 20 kg. Flexion angle in PIP measuring 90º

Loading included a ball grip with a flexion of 0, 30, 60, 90 degrees in the PIPJ and compression of the object. The loads ranged between 1 kg and 20 kg. The magnitude of the load applied was chosen based on literature data showing the maximum loads at which critical conditions occurred in real clinical conditions [30]. For demonstration purposes, the figures show only one type of the load applied as an example.

The clinical picture and range of motion in the operated joint were evaluated in addition to digital modeling of critical conditions using the finite element method. Our series included 10 patients who underwent endoprosthesis of the proximal interphalangeal joint for post-traumatic arthritis; the maximum follow-up period was 6 months.

RESULTS

The correlation between stresses in bone tissue and the loads applied is shown in Figure 6.

Analysis of critical loads simulated in PIPJ showed:

– the stability of the biomechanical construct being not impaired at any flexion (0°, 30°, 60°), except 90° with a load of up to 5 kilograms;

– cortical bone tissue can withstand loads of up to 20 kilograms at any flexion (except for a flexion angle of 90°);

– the biomechanical construct remained stable at flexion of 0-30° with loads of up to 20 kilograms;

– the strength of the implant elements significantly (more than 2 times) exceeded the strength of the bone tissue in the “implant – bone tissue”.

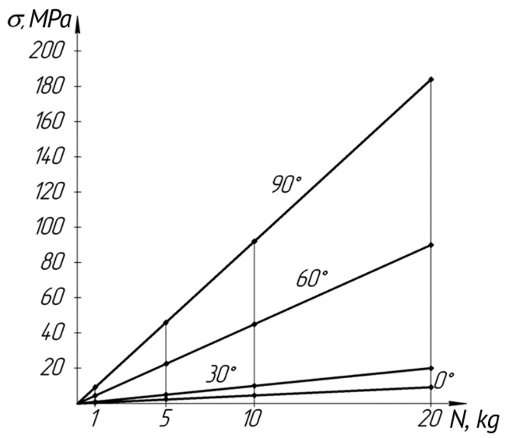

Fig. 6 Correlation between stresses in bone tissue and the loads applied

DISCUSSION

Trauma and orthopaedic surgery is a rapidly advancing and evolving branch of medicine with new methods of diagnosis and treatment of various pathologies being introduced daily. A number of technologies have changed the way that joint replacement surgeries are done: robot-assisted knee replacement has already become routine practice in the United States. Over 100,000 joint replacements are performed annually in Russia, and more than 90 % of the number include large joints: hip, knee, shoulder [21]. Modern lines of implants for large joints facilitate treatment of osteoarthritis of various stages, taking into account technical difficulties and patient comorbidity using arthroplasty as a routine, universal and absolutely accessible medical service [22, 23]. Despite the great successes achieved in surgery of large joints, replacement of small joints of the hand and foot fails to provide an optimistic picture. The complex geometry and biomechanics of the joints, the limited stock of bone and periarticular tissues, high demands placed on the hand by the patient make outcomes of hand joint replacement contradictory and debatable [24, 25]. The hand is one of the most complex organs with the largest representation in the central nervous system and high human demands. Restoring fine motor skills of the fingers, the need to perform strictly apportioned movements in everyday life is a real challenge for the team of specialists involved in the treatment of diseases and injuries of the hand. Finger replacement implant design continues to evolve as past implants have had variable success [26, 27, 28, 29]. An anatomically adapted PIP joint based on an analysis of biomechanics and radiological data from 42 patients with different degenerative diseases was simulated at SamSMU between 2016 and 2021. We simulated the biomechanics that occur in real clinical conditions in order to reduce the rate of complications associated with the use of endoprostheses. This is a pilot research in the industrial implantology in the Russian Federation.

Modeling of real biomechanics is essential to avoid critical clinical conditions and physical and psycho-emotional trauma. Simulation suggests an abstraction from the actual use of an endoprosthesis in a patient and gives us the opportunity to determine the boundary conditions for the use of the implant. The finite element analysis demonstrated the greatest stresses being experienced by the "implant – bone tissue" zones with the exception of the model having a flexion angle of 00 in the PIPJ. Greater stresses are observed at the flexion angle of 00 in the PIPJ of the endoprosthestic components. Bone tissue appeared to be the most loaded material and most susceptible to destruction. The prospects of the research can include the development of a "weak link" preventing bone destruction by stress concentrators introduced into the implant components. The endoprosthesis will be subject to destruction with the extreme loads.

Strength tests performed in patients after replacement of the proximal interphalangeal joint will be practical to avoid the risk of critical complications including dislocation of endoprosthetic components, fracture of the stem and periprosthetic fracture.

The digital model offered had drawbacks that were acceptable for experimental research and for the modeling process [30]. The Ansys software package could identify the implant as a simplified model to allow mathematical calculations and abstraction of the process from the real clinical scenario. The principle can be employed for complex preclinical trials with no clinical conditions provided at the stage. Nevertheless, we could achieve our goal and analyze the maximum loads on the implant measuring the strength characteristics of bone tissue and zirconium ceramics as a material. The study was aimed to develop an optimal mode of physical activity early after surgery and an optimal range of motion after PIPJ arthroplasty.

The interdisciplinary research is essential for developing a new endoprosthetic design using new materials and their combinations. We used the results of the study in the postoperative management of 10 patients with a maximum follow-up period of 6 months. Mathematically calculated loads allowed for 49 to 70 degrees of flexion achieved in the involved joint during rehabilitation. There were no complications associated with critical conditions of the endoprosthetic joint: fractures of the stem, periprosthetic bone fracture, joint instability.

CONCLUSION

A load of 5 kg or less applied early after surgery was shown to be optimal for the patient with flexion angle being 90° or less. The patient could use a load weighing 5 to 20 kg with the flexion angle of 30° or less in the proximal interphalangeal joint. The risk of endoprosthetic dislocation is greater with a load of 20 kg and a flexion angle of more than 30°, and a periprosthetic fracture can occur at a flexion angle measuring more than 60°.

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Nikolaenko A.N. – control, project management.
Zgirskii D.O. – research, writing (original version, editing, visualization).
Doroganov S.O. – visualization, writing – editing.