ISSN 0030-5987. Orthopaedics, traumatology and prosthetics. 2021. № 4

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УДК 616.728.2+616.728.3]-089.843-77(045)

DOI: http://dx.doi.org/10.15674/0030-59872021470-78

Modern trends in the developments of hip and knee arthroplasty

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Total hip (THA) and knee (TKA) arthroplasty is an effective surgical treatment for late-stage osteoarthritis. Objective. Highlight the most significant technological developments in the design of implants and assistive technologies for hip and knee arthroplasty. Results. The development of hip and knee arthroplasty is associated with the desire to improve treatment outcomes, reduce complications and increase the survival of implants. The emphasis is placed on some of the most interesting, in our opinion, trends in this area. It has been shown that metal-to-metal friction steam implants are used to replace the articular surface of the hip joint, but the method is the best option only for active men with a large hip joint. New approaches involve the use of friction pairs «ceramic – ceramic» or «metal – polyethylene». The creation of smaller femoral components of endoprostheses (mini-legs) for THA is aimed at preserving bone tissue and achieving physiological load. Dual mobility endoprostheses are increasingly preferred for primary THA. The creation of implants with a porous surface (in particular, with the use of additive technologies) is promising to increase their osteointegration and antibacterial properties. The latest direction is the creation of robotic support systems for joint replacement operations, which will improve the accuracy of implant positioning, reduce blood loss, improve functional results, as well as achieve after TKA balance of ligaments and joint space by accurately determining its size and accuracy resection of the femur. However, high-evidence clinical trials are needed to find convincing long-term results for this approach to become standard in hip and knee arthroplasty. Conclusions. Robotic surgery is one of the most interesting developments in hip and knee surgery. The growth in the use of this technology has shown convincing long-term results. Key words. Orthopaedics, hip arthroplasty, total knee arthroplasty, osteoarthritis, robot-assisted surgery.

Тотальне ендопротезування кульшового (ТЕК) та колінного суглобів (ТЕКС) є ефективним хірургічним методом лікування остеоартрозу на пізніх стадіях. Мета. Висвітлити найзначніший технологічні розробки щодо дизайну імплантатів і допоміжних технологій для ендопротезування кульшового та колінного суглобів. Результати. Розвиток ендопротезування кульшового та колінного суглобів пов'язаний із прагненням покращити результати лікування, зменшити ускладнення та підвищити виживаність імплантатів. Акцентовано увагу на деяких найцікавіших, на нашу думку, тенденціях у цій галузі. Показано, що для заміни суглобової поверхні кульшового суглоба використовують імплантати з парою тертя «метал – метал», але метод є оптимальним варіантом лише для активних чоловіків із великим кульшовим суглобом. Нові підходи передбачають застосування пар тертя «кераміка – кераміка» або «метал – поліетилен». Створення менших стегнових компонентів ендопротезів (мінініжок) для ТЕК спрямовано на збереження кісткової тканини та досягнення фізіологічного навантаження. Ендопротезам із подвійною мобільністю все частіше віддають перевагу для первинного ТЕК. Перспективним є створення імплантатів із пористою поверхнею (зокрема, і з використанням адитивних технологій) для підвищення їхніх остеоінтеграційних і антибактеріальних властивостей. Новітнім напрямом є створення роботизованих систем супроводу операцій ендопротезування, що дасть змогу покращити точність позиціонування імплантатів, зменшити крововтрату, покращити функціональні результати, а також досягти після ТЕКС балансу зв'язок і суглобової щілини завдяки точному визначенню її розмірів та точної резекції стегнової кістки. Проте необхідно провести клінічні дослідження з високим рівнем доказовості для виявлення переконливих довгострокових результатів, щоб цей підхід став стандартом в ендопротезуванні кульшового та колінного суглобів. Висновки. Роботизована хірургія є однією з найцікавіших розробок хірургії кульшового та колінного суглобів. Проте необхідні подальші дослідження в цьому напрямі. Ключові слова. Ортопедія, ендопротезування кульшового суглоба, тотальне ендопротезування колінного суглоба, остеоартрит, робото-асистована хірургія.

Key words. Orthopaedics, hip arthroplasty, total knee arthroplasty, osteoarthritis, robot-assisted surgery

Introduction

Total hip and knee arthroplasty is an effective surgical treatment for osteoarthritis. Replacement surgery involves resection of the degenerative joint and replacement with synthetic components that reconstruct worn surfaces of the joint, allowing early painless mobilization. The design and improvement of hip and knee implants over the past century have focused primarily on reducing mechanical wear and improving fixation. This approach has been very successful in creating friction surfaces and implant coating materials, providing much more durable solutions than those available during the first hip and knee arthroplasty operations in the 1960s.

Representatives of modern humanity are characterized by longer life expectancy, prolonged physical activity, which affects the tendency to replace the joints earlier. Therefore, work to improve the survival of implants remains relevant. However, more and more developments in hip and knee arthroplasty technology are focused on methods that are expected to improve the patient's condition and treatment outcomes through a strategy of simulating more natural kinematics and optimized implant placement. In this paper, we focused on highlighting the most significant technological developments in the design of implants and assistive technologies in hip and knee arthroplasty.

Hip resurfacing

Replacement of only the articular surface of the hip joint is an area that should be considered as a new technology, given that implants are used in various variations for more than 40 years [1]. Surgery to replace the articular surface of the hip joint provides an alternative to more traditional endoprosthetics for the treatment of osteoarthritis. Such surgical manipulation (Fig. 1, a) allows to preserve the bone tissue of the femur in contrast to the classic total arthroplasty. The larger size of the femoral head component results in a more biomechanically stable connection [2]. However, the use of large metal structures has some drawbacks: these implants show high revision rates, usually due to the formation of metal microparticles, which cause side effects in some patients. Increased rates of revision interventions negatively affected the perception of replacement of the articular surface of the hip joint.

However, this method shows a lower level of dislocations and higher for functional results for young active patients compared to total hip arthroplasty [3, 4]. At the same time, replacement of the joint surface using metal-metal friction pair implants remains the best option for active men with a large hip joint, but is no longer considered for men with smaller femoral heads and never for women. New approaches to solving this problem involve the use of friction pairs «ceramic-ceramic» (Fig. 1, b) or «metal-polyethylene» (Fig. 1, c).

Today, there are at least two types of ceramics to replace the joint surface, which are undergoing early clinical trials. H1 ceramics — non-porous for cementless joint surface replacement – developed by Embody Orthopedic Limited (London, UK) are currently being evaluated in a multicenter observational study launched in September 2017. The aim of this ten-year controlled study is to analyze the safety and effectiveness of prosthetics. The ReCerfTM Ceramics-Ceramics pair, developed by MatOrtho (Letterhead, Surrey, UK), is currently awaiting certification in the UK, although the first product was implanted on 24 September 2018. No early clinical data are available for any of these materials, but biomechanical studies on the bodies demonstrated comparable deformations in the case of installation of standard metal and the latest ceramic ReCerfTM acetabular component of the endoprosthesis [5].

Although the ceramic-ceramic joint pair does have favorable wear characteristics, there are concerns about the creaking and fragility of ceramic supports. In addition, there may be an undesirable decrease in bone density around implanted ceramic elements — a phenomenon known as stress shielding [6]. To address this potential problem, a metal-cross-linked polyethylene (MoX) friction pair has been developed to replace the articular surface of the hip joint. Currently, more than a hundred MoX products have been implanted [7]. This joint vapor has the potential to minimize the release of metal ions, and lower polyethylene stiffness reduces the risk of stress shielding compared to harder acetabular components, although at the same time may increase the volume wear of polyethylene [8].

Short-stemmed implants in total hip arthroplasty

As a result of the refusal to replace the articular surface of the hip joint with «metal – metal» and the growing popularity of minimally invasive surgical approaches, there is a tendency to create smaller femoral components of endoprostheses (Fig. 2), aimed at preserving bone tissue and more physiological load on the proximal femur [9].

The differences between the philosophies and design of short-stemmed implants reflect the complexity of systematic research and meta-analysis of their use [10]. In particular, S. Lidder et al. [11], based on an analysis of 15 studies, demonstrated

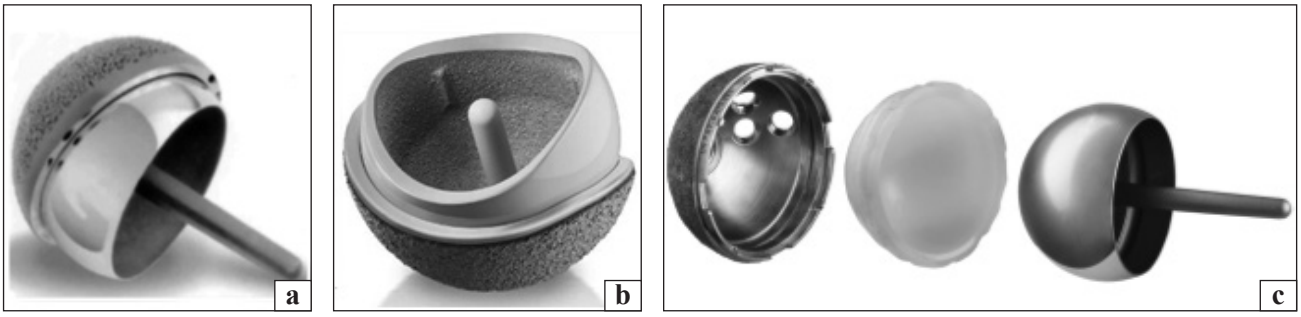

Fig. 1. a) Joint pairs to replace the articular surface of the hip joint: «metal-metal» by Birmingham; b) «ceramic-ceramic» H1® (Embody, London, UK); c) «metal-cross-linked polyethylene» (according to [3])

Fig. 2. Tri-lock short-stemmed implant for total hip arthroplasty [13]

implant preservation in 98.6 % of cases over an average of 12 years. However, the training of specialists for the use of short-stemmed implants is longer compared to routine total hip arthroplasty, and the need for stable press fit fixation requires reducing the number of errors in implant placement and improving surgical techniques [12]. A recently published randomized 2-year radiometric study determined the stability of short-stemmed implants that was lower than standard-length ones, namely the migration of femoral components of endoprostheses [13].

Total hip arthroplasty with a dual mobility implant

The use of dual mobility joint endoprostheses, although not the latest method (first proposed by Gilles Bousquet in 1974 [14]), has increasingly been preferred in recent years for primary total hip arthroplasty [8]. Dual mobility implants (Fig. 3) consist of a small metal or ceramic head that is closed but mobile inside a larger polyethylene head, which in turn connects to the acetabular portion of the endoprosthesis. Based on the analysis of the national joint registries of different countries, the tendency to increase the use of dual mobility connections has been determined. In particular, a study of the American Joint Replacement Registry found an increase in the use of these implants to 6.9 % of the total number of hip arthroplasty [15]. There have even been proposals to use dual mobility endoprostheses as the main alternative to traditional implants [16]. Given the improvement in the stability of implants with dual mobility, it is necessary to study the impact of adverse lumbar-pelvic mobility and its consequences and the development of dislocations of total hip arthroplasty. There has been an increase in the use of these implants in patients with impaired neuromuscular system or cognitive disorders [17]. However, there are problems with polyethylene wear, intra-articular dislocations, and limited publication on the long-term survival of polyethylene endoprostheses [18]. Today it is known that the average annual wear of double-mobility liners is 38 mm^3/year, which does not exceed that of similar cement implants [19].

Dual mobility endoprostheses have been successfully used to revise the femoral component with a large head in a metal-metal friction pair during hip prosthetics [20]. Such implants show a higher survival rate after revision operations compared to standard (fixed-bearing) implants [21].

Cementless total knee arthroplasty

One of the most promising areas in the creation of implants for knee arthroplasty is the cementless method of fixation. Traditionally, endoprostheses for total knee arthroplasty are fixed with polymethyl methacrylate cement, which is connected to the spongy bone of the recipient. Cement-free total knee arthroplasty has an important advantage — the ability to avoid additional substance in the area of interaction «bone-implant» in the hope of reducing the rate of wear and loosening of structural elements. However, at the beginning of the use of this technique against the background of perfect fixation of the femoral component of the endoprosthesis was observed 8 % aseptic loosening of the tibial implant and the formation around it or screws small foci

Fig. 3. Total dual mobility hip endoprosthesis [18]

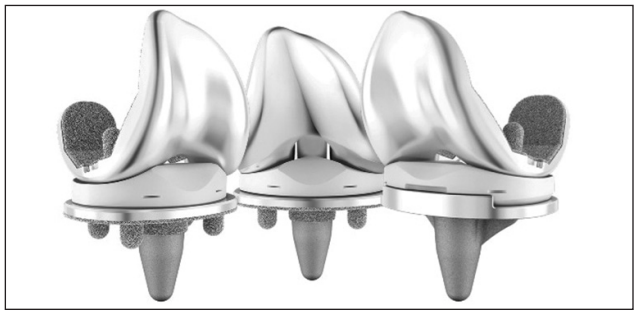

Fig. 4. Cementless knee arthroplasty Attune Johnson & Johnson (according to [27])

of lysis (12 %) with a mean follow-up of 11 years. The frequency of revision of the knee component reached 48 %. This was the reason for refusing to use the technology [22].

Recent research in the field of cementless technology and design has led to the creation of a new generation of porous implants for cementless total knee arthroplasty. This helped to draw attention to this technique. After conducting a randomized controlled trial involving 147 patients, which lasted an average of 2 years, no difference was found in early and long-term radiological and clinical results in the case of cement and cementless knee arthroplasty. It should be noted that age over 75 years, body mass index over 40 kg/m^2, osteoporosis or bone defects were the exclusion criteria from the study [23]. J. M. Newman et al. [24] performed a meta-analysis of studies published in 2000–2017, which compared the functional results, survival of implants after primary cementless and cement knee arthroplasty with an average follow-up of 6 years. The best survival of cementless implants was revealed against the background of no differences in functional results and range of motion in the joints. However, only 7 works were included in the meta-analysis, which leads to additional randomized trials to obtain convincing evidence in favor of cementless technology. The relatively selective nature of research on implants for cementless knee arthroplasty limits the certainty about their feasibility for the general population [25].

Cementless technology can be successful for single-knee knee arthroplasty. Cementless partial replacement of the OxfordVR® knee joint by Zimmer Biomet has demonstrated excellent survival [26]. However, after the installation of cementless structures during knee arthroplasty, many young patients received unsatisfactory results due to significant lysis and loss of bone tissue [5]. Overall, the initial results of using a new class of implants for cementless knee replacement are encouraging, although further lengthy research is needed before this technology replaces the cement technique.

Modification of the implant surface

The shape of endoprostheses, which corresponds to the anatomical structure, biomechanics and physiological functioning of the joints, is an extremely important component of the success of surgical treatment of patients with stage III-IV osteoarthritis. However, due to the increasing incidence of periprosthetic infection and in order to improve osseointegration, more and more research is being done to modify the physical (surface relief, porosity) and chemical properties of implants.

Currently, titanium alloys, mostly Ti-6Al-4V, are often used in orthopedics due to bioinertness, biocompatibility, required biomechanical properties and ease of surface modification [28]. To improve osseointegration and long-term stability of implants, researchers have focused on creating the latest coatings and methods of their application, such as sandblasting or the use of plasma spraying [29].

Recognition of potentially positive effects of nanorelief on the surface of implants on their stability and functionality led to the development of methods for its modification. These approaches include methods such as electron beam lithography, anodizing, and 3D printing, which allow the creation of nanoscale tubes, pits, pores, and columns on the implant surface, which will improve osteoconduction and osseointegration. In addition, nanostructured modified materials (in particular, titanium and its alloys) are also considered in the context of the ability to minimize bacterial adhesion, inhibit biofilm formation and ensure bacterial destruction [30, 31]. Since the discovery of the adverse effects of biofilms that cause bacterial infections on the surface of implants [32], attractive approaches have been developed to solve this problem by creating nanostructured coatings or elution with bactericidal ions such as silver. In vitro experiments have shown that nanorough surfaces of titanium formed by electron beam deposition reduce the adhesion of S. aureus, S. epidermidis, Pseudomonas aeruginosa, which are responsible for more

than 50 % of cases of periprosthetic infection. This is due to increased absorption of fibronectin, which stimulates the attachment of osteoblasts and, consequently, the formation of new bone [33]. Cell culture has also shown that nanomatrices created on the surface of titanium by hydrothermal digestion have a selective bactericidal effect, reducing almost 50 % of attached Pseudomonas aeruginosa cells and about 20 % of S. aureus. Instead, the attachment and proliferation of primary human fibroblasts increases within 10 days of growth [34]. The determined properties of titanium nanorough surfaces give hope that they can be prevented if they are used to develop bacterial colonies on implants in the early postoperative period, which will reduce the risk of such a threatening complication of endoprosthetics as bacterial infection.

An alternative to modifying the surface structure of the implant is the local release of antibiotics from the array of nanotubes and synthetic polymers of lactic and glycolic acids, the use of silver as an antibacterial coating, etc. [35]. Non-antibiotic antibacterial coatings are the most studied silver nanoparticles. They are released into the peri-implantation space and, penetrating into bacterial cells, destroy them. In particular, low concentrations of silver ions have been shown to be effective against S. aureus for 10 days of cultivation [36]. However, high concentrations of silver ions can have a cytotoxic effect. These technologies are under development and study, but are likely to find practical application [37].

Additive production and individual implants

For the most part, standard components are used during endoprosthesis surgery to satisfy most patients and surgeons. The production of individual endoprostheses for the reconstruction of the hip and knee joints will increase the effectiveness of surgical treatment in case of complex revision interventions in patients with significant bone loss, removal of tumors and reconstruction of defects after serious injuries. With the development of technology, the individual cost of endoprosthesis decreases, so the demand for personal implants is expected to increase [38]. Their production for total hip arthroplasty is aimed at reducing the stress load due to the conformity of the arthroplasty to the anatomical features of the patient, as well as more accurate restoration of the center of rotation of the joint. Implants were originally made on the basis of standard X-rays using standard Computer Numerical Control (CNC) with mechanical treatment before coating to promote osseointegration. Analysis of the results of a series of individual femoral components of hip arthroplasty made by this technology showed the survival of 98.2 % of them after 13.2 years on average, which can be compared with the best standard components of the thigh [39]. In a similar study, E. Dessyn et al. [40] showed 96.8 % survival of individual stems in 20 years after surgery and 94.5 % in 25.

Recent additive manufacturing technologies have simplified the manufacture of complex individual implants, including porous structures with variable density and stiffness, to minimize bone resorption due to stress [41]. Experience with the use of special additive implants is associated with revision operations to replace the acetabular component. A recently published review of scientific publications based on the results of 17 studies on the use of a special triflange acetabular component showed that the overall incidence of complications was 29 %. Dislocation (11 %) was most often observed, followed by infectious complications (6.2 %), nerve damage (3.8 %), aseptic loosening (1.7 %) [42]. These complex cases have demonstrated results that are comparable to other reconstructive options. Although these non-standard solutions often seem an attractive option for severe cases, it should be remembered that due to their individuality, it is not possible to create a homogeneous study group to compare with groups of patients with implanted standard endoprostheses. Since 2002, the Orthopedic Data Evaluation Panel (ODEP) has classified the results of standard arthroplasty as safe and effective, and has also established benchmarks for the latest implants. However, such an assessment is not available for individual endoprostheses, so surgeons should inform patients of the lack of implant survival rates.

Robotic surgery

Decisions on the intraoperative placement of components for knee and hip arthroplasty have traditionally been based on anatomical landmarks and anchor points for component placement. One of the most exciting advances in joint arthroplasty is the use of robotic systems that make it easier for surgeons to make critical decisions. Such systems began to be used in the 1980s [43]. Robotic surgery is the evolution of navigational arthroplasty, where computer support helps to best position instruments and implants. The next step is for the robot to help position the instruments or control their function to ensure that the bone is resected as planned. The surgical plan can be based on the anatomical features of a particular patient, which are determined by computed tomography.

Significant growth in the use of robotic surgery has occurred in the United States in the last

decade. In the New York region in 2008–2015, slightly more than 5% of all hip and endoprosthetic procedures were performed with robotic or navigational aids [44]. The desire to increase the use of robotic technologies has influenced the involvement of leading manufacturers of hip and knee implants: Mako SYSTEM from Stryker, Navio/BlueBelt from Smith & Nephew, ROSA from Zimmer Biomet are becoming more affordable.

There is strong evidence that robotic surgery can help improve the positioning accuracy of implants compared to manual when performing total hip and knee arthroplasty. A statistically significantly higher number of acetabular components located within 5° of the target alignment was demonstrated in the case of robotic navigation [45]. Similar results were obtained from the observation of 300 patients, 100 of whom underwent total hip arthroplasty using a robotic system [46].

S. W. Bell et al. [47] conducted a randomized study involving 120 patients and reported increased implant placement accuracy with robotic surgery compared to standard techniques in single-knee arthroplasty. Several other studies on the use of robotic systems during single-joint and total knee arthroplasty have also shown an increase in the accuracy of implant placement under these conditions [48–50]. In the case of knee arthroplasty, the use of robotic support allows to achieve in the postoperative period the balance of ligaments and joint space by accurately determining its size and accurate robotic resection of the femur [51].

Other advantages of robotic surgery include: less intraoperative blood loss and better functional performance on the HHS, WOMAC scales for 1.5 years after total hip arthroplasty [52]; soft tissue protection compared to manual methods [53]. However, in general, there is little data to suggest that excellent functional results can be expected with this technology. In a meta-analysis of S. Karunaratne et al. [54] evaluated the results of 14 studies of robotic knee and hip arthroplasty and found no difference between functional results compared to manual surgery. None of the included studies showed significant differences in the level of pain, quality of life or satisfaction with surgery. Other authors also did not differentiate between the groups of robotic and manual single-growth knee arthroplasty based on functional outcomes, frequency of revision operations, or range of motion [55].

Robotic surgery is associated with additional costs for the purchase of equipment, special radiological examinations, increased operation time. Given the uncertain clinical benefits, cost-effectiveness has become a barrier to the wider adoption of this technology. However, studies have shown that large patient centers (over 1,000 per year) that use robotic surgery can be cost-effective for single-knee arthroplasty [56]. In any case, further research in this area will continue.

Conclusions

In this review, we focused on some of the most interesting, in our opinion, strategies and developments in hip and knee arthroplasty, as well as the use of robotics for such surgical interventions. Although these developments focus on specific aspects of joint arthroplasty, they are common in their overall goal of improving patient outcomes. Given that most classic arthroplasty operations have provided excellent long-term results, only an evaluation of robotic surgery from a qualitative randomized trial at Evidence Level 1 or 2 can yield convincing long-term results to justify its adoption as standardized modern arthroplasty technology.

Conflict of interest. The authors declare no conflict of interest.

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The article has been sent to the editors 01.11.2021

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