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Review article

HIP JOINT AND HIP ENDOPROSTHESIS BIOMECHANICS

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ABSTRACT

This article contains a description of the basic issues related to anatomy, loading of hip joint and its endoprosthesis research methods. The methods of testing and simulating hip joint loads, factors that influence the selection of parameters during the design of prostheses, typical solutions to engineering problems related to this topic are presented. The article concludes with short summary of the finite element method for the design of hip replacements.

KEYWORDS: hip joint, hip joint endoprosthesis, biomechanics of lower limb, total hip replacement

BIOMECHANIKA STAWU BIODROWEGO I JEGO ENDOPROTEZY

STRESZCZENIE

Artykuł zawiera opis podstawowych zagadnień związanych z anatomią, obciążeniami i metodami badawczymi dotyczących stawu biodrowego oraz jego endoprotezy. Przedstawione są sposoby badania i symulowania obciążeń w stawie biodrowym, czynniki wpływające na dobieranie parametrów podczas projektowania endoprotezy oraz typowe rozwiązania problemów inżynierskich związanych z tym tematem. Artykuł zakończony jest krótkim streszczeniem zastosowań metody elementów skończonych podczas projektowania endoprotezy stawu biodrowego.

SŁOWA KLUCZOWE: staw biodrowy, endoproteza stawu biodrowego, biomechanika kończyny dolnej, całkowita wymiana stawu biodrowego

1. Introduction

The modern research of biomechanics of human hip joint started in the nineteenth century when Julius Wolff depicted the relation between the inner structure of the bone and the outer functional loading. Years later Friedrich Pauwels studied the biomechanics of join loading, allowing him to create model of hip joint load (Fig. 1). His research referred to various joint positions and their influence on muscle forces related to them [1], [2].

Those studies are still relevant nowadays, as they were the bases for developing the first hip joint endoprothesis. Considering total hip replacement influences all joint parameters including: range of motion, joint centre, neck angle, offset, lever arms, there is still a constant need of improvement of biomechanical models. Mainly, due to the fact that hip joint is one of the most liable structure to overstrain in human body as a result of its main role in carrying bodyweight. The following paper describes different approaches in engineering towards hip endoprosthesis, and biomechanics related to hip joint [1], [3].

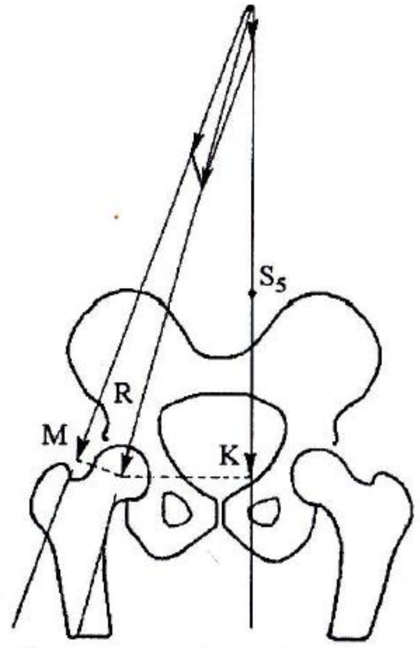

Fig. 1. Pauwels' model of hip joint load [2]

2. Anatomy of hip join

The hip joint (Fig. 2) is a movable connection of the acetabulum of the pelvis and the femur. The curvature of surface of the hip joint is the most regular one of all the joints in the human body. The hip joint allows a wide range of movements as it consists of ball and socket joints. The femoral head has a spherical shape with a radius of 12,5 mm. Surface of the bones is covered with hyaline cartilage. The joint capsule is a short, narrow bag, which is twisted and heavily strained when a human is in upright posture. The hip has to support the entire body, and at the same time, has the motor functions, thus it requires special ligament supporting the joint bag [4-6].

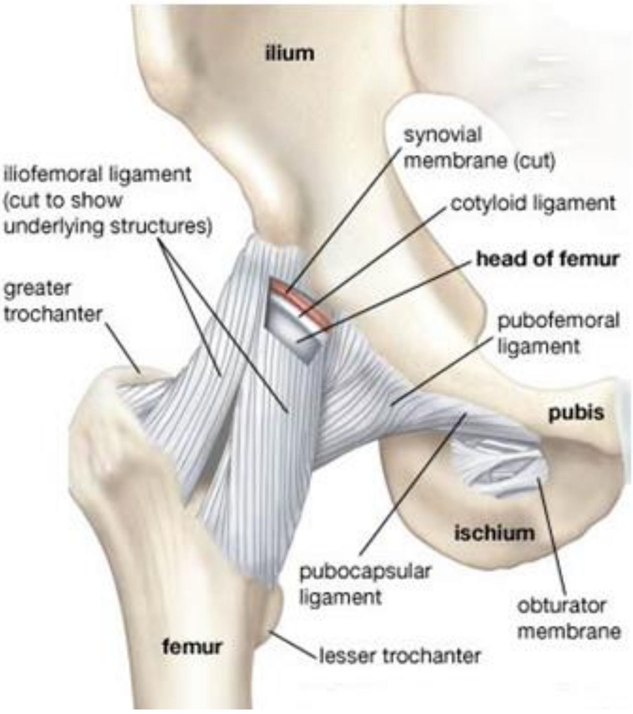

Fig. 2. Anatomy of hip joint [7]

3. Hip joint biomechanics

One of the basic goals of biomechanics is to calculate the loads occurring in the bones and muscles of a human body. Unfortunately, measuring muscle forces and joint loads is still problematic. Nowadays, three following methods of determining the loads in human musculoskeletal system can be distinguished:

- Implant based methods.
- Mathematical models based on electromyography (for determining muscle reaction forces).
- Mathematical models of human movement, using optimisation techniques to identify muscle forces.

The most precise and accurate method is the implant based one. Professor George Bergman constructed hip joint endoprosthesis (Fig. 3) containing sensors which allow to gather data about the direction and value of forces occurring in the hip. This device was also fitted with telemetric transmitter which was used to remotely send the data to the computer. This method was later applied to other joints such as the knee joint, shoulder joint or even in the spine [8].

Fig. 3. Professor's Bergman hip joint endoprosthesis [8]

Maximum values of reaction forces measured by this kind of implant did not exceed 400% of bodyweight of the patient (Fig. 4). In 2001 professor Bergman concluded that the average hip joint load during normal gait was 238% BW based on his data collected from 4 patients [2], [9].

This method requires surgical operation and usually is applied on patients requiring arthroplasty, significantly reducing the amount of such procedures. Moreover, this method examines only one joint at the time, the one where the endoprosthesis is implanted [8].

Other methods can rely on simulating ground reaction force varying on different initial conditions and equations to obtain a graph of function describing the change of ground reaction force in time. This graph can be further used in development of studies regarding stress distribution in entire lower limb [10].

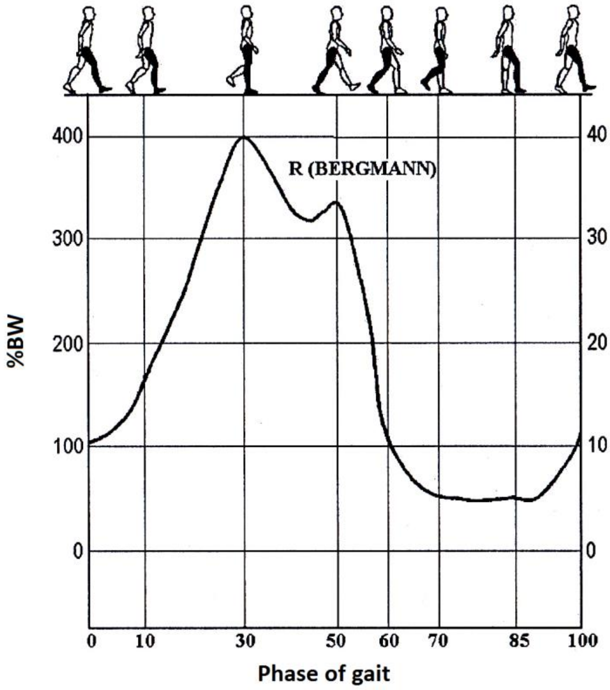

Fig. 4. Percentile contribution of body weight (%BW) in loads carried by the hip joint [2]

4. Design of endoprosthesis

The most important aspects during engineering the endoprosthesis are:

- range of motion,
- impingement implant fixation,
- tissue damage during implantation and tissue tension after total hip replacement,
- component orientation (stem, cup),
- bearing material.

Most of this factors deal with loosening of the prosthesis component, or its dislocation [1].

Range of motion depends almost entirely on prosthesis design. Part of the endoprosthesis placed in the femur can differ in shape, length, surface structure, varying on used material and fixation method. This part is topped with spherical head placed in acetabular component. Figure 5 shows the variety of used prosthesis.

Fig. 5. Different hip joint endoprosthesis designs (from left to right: Zweymüller, Exeter, Corail, St. Georg, Silent & Resurfacing, CFP, Meta, Charnley) [1]

Usually, the acetabular cup reassembles half of the sphere and its function is similar to anatomical. It restricts the diameter of the prosthesis head. The cup made of ultra-high molecular weight polyethylene (hirulen), ceramics or metal is inserted in the metallic shell (CoCrMo, titanium, stainless steel), which is later attached to the pelvic bone. Heads are usually made of stainless steel, CoCrMo, zirconium or aluminium ceramics, titanium alloy and single crystal sapphire. Head size determines range of motion, although in reality patient's condition and orientation of the components affects it more. Taking into consideration aforementioned reasons change of diameter of the head from 28 mm to 36 mm can increase the range of motion by 13° [1], [11].

Modern prosthesis models are often created in computer aided environment, for instance in Solid Works, Solid Edge (Fig. 6) or Catia. CAD significantly reduces the time needed to create the project. Dimensions of the entire set are based on images gathered from MRI or computer tomography, and are consulted with clinician, which aims for best fixation in patients' bones [12], [13].

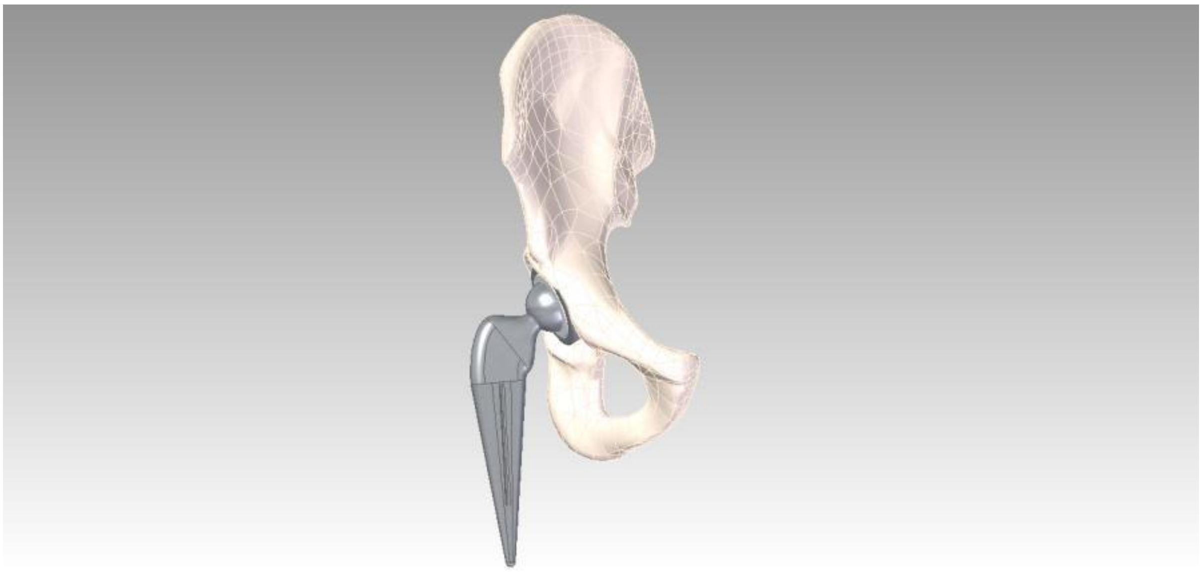

Fig. 6. Model of endoprosthesis mounted in pelvic bone in virtual environment of Solid Edge ST8 [12]

Creating virtual model in most of CAD programs allows to extrapolate the predicted properties of prosthesis using finite element analysis. FEM divides geometric models into finite amount of subareas (for example triangles) connected by nodes. This creates discrete geometric model, all the other variables such as loads are also discretised and put into equations for specific elements. After creating stiffness matrix, applying boundary conditions, initial conditions and loads the program proceeds to the solution phase, where nodal results are calculated. The application of FEM can be crucial in the design process, but It should be taken into consideration that this process only approximates the results, and relies heavily on used method and pre-selected conditions [12], [14].

For instance FEM (Fig. 7) can be used to determine more suitable material for endoprosthesis socket inlay and head, depending on bodyweight force percentage applied to them. Choosing the right material may be the significant element of designing hip joint endoprosthesis, as worn material expelled from prosthesis surface can lead to major malfunctions and force revision surgery [15], [16].

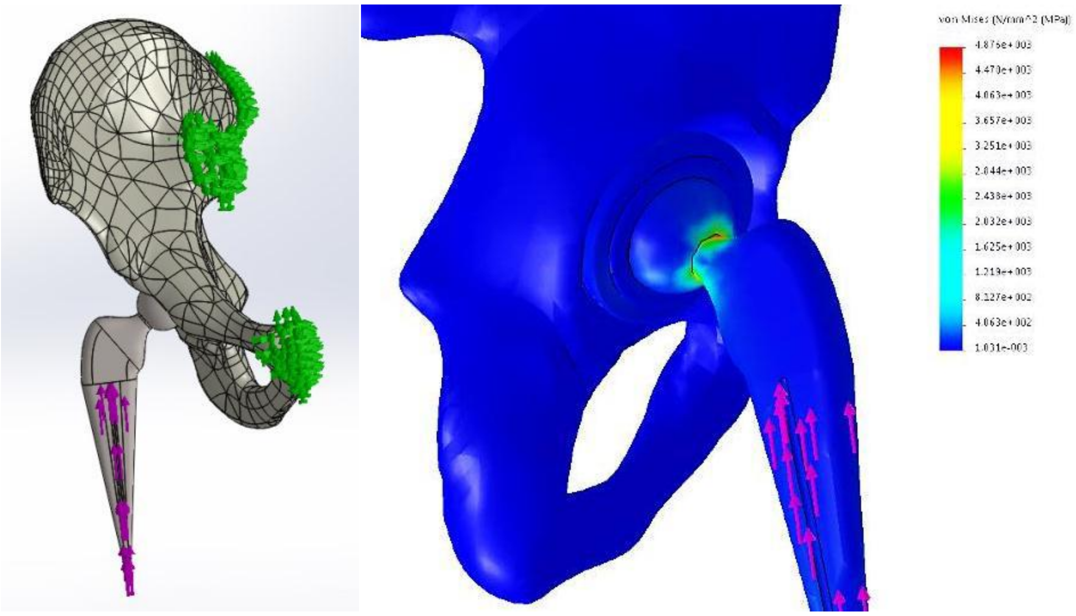

Fig. 7. Fixation points and results of FEM analysis of hip joint endoprosthesis [12]

5. Summary

The progress observed in the technology in last 20 years may indicate on further development in the field of biomechanics of hip joint, as well as its endoprosthesis. More precise and realistic FEM simulations would be possible thanks to the more powerful computers, thereby the minimization of telemetric systems should lead to safer, cheaper and more accessible data acquisition. The development in the field of biomaterials could change the way the endoprothesis are designed. This may be the reason for the great scientific focus on this subject in the recent academic works.

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