



ORIGINAL

Effect of changes in the centre of rotation after hip arthroplasty on knee joint function

Efecto de los cambios en el centro de rotación tras una artroplastia de cadera sobre la función de la articulación de la rodilla

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ABSTRACT

Introduction: a common complication after hip arthroplasty is pain and inflammation in other large joints, especially the knee joint. Displacement of the centre of rotation of the femoral head after endoprosthesis can change the redistribution of force vectors acting on the femur, change its tilt and pressure on the surface of the knee joint.

Objective: the investigation of the effect of displacement of the centre of rotation of the hip joint after arthroplasty on the knee joint.

Methods: using SolidWorks software and the SimulationXpress tool, a 3D model of the lower limb was created that reproduced the interaction between the components of the musculoskeletal system.

Results: as a result, it was found that the displacement of the centre of rotation of the hip joint medially and laterally from the anatomical position leads to a significant increase in pressure on the corresponding tibial condyles. The increase in load is linear and increases from a minimum value of 1,77 N·m in anatomical position to 123,79 N·m with a medial displacement of up to 8 mm.

Conclusions: this study indicates the need for proper restoration of the centre of rotation of the hip joint after implantation and the possible consequences of changes in knee joint loads. The data may be useful for specialists working in the field of implantology and the development of hip prosthesis systems.

Keywords: Osteoarthritis; Tibial plateau; Prosthesis; Load.

RESUMEN

Introducción: una complicación frecuente tras la artroplastia de cadera es el dolor y la inflamación en otras articulaciones grandes, especialmente la articulación de la rodilla. El desplazamiento del centro de rotación de la cabeza femoral tras la endoprótesis puede modificar la redistribución de los vectores de fuerza que actúan sobre el fémur, cambiar su inclinación y ejercer presión sobre la superficie de la articulación de la rodilla.

Objetivo: investigar el efecto del desplazamiento del centro de rotación de la articulación de la cadera tras la artroplastia sobre la articulación de la rodilla.

Métodos: utilizando el software SolidWorks y la herramienta SimulationXpress, se creó un modelo 3D de la extremidad inferior que reproducía la interacción entre los componentes del sistema musculoesquelético.

Resultados: como resultado, se observó que el desplazamiento del centro de rotación de la articulación de la cadera medial y lateralmente con respecto a la posición anatómica provoca un aumento significativo de la

presión sobre los cóndilos tibiales correspondientes. El aumento de la carga es lineal y aumenta desde un valor mínimo de 1,77 N·m en posición anatómica hasta 123,79 N·m con un desplazamiento medial de hasta 8 mm.

Conclusiones: este estudio indica la necesidad de restablecer adecuadamente el centro de rotación de la articulación de la cadera tras la implantación y las posibles consecuencias de los cambios en las cargas de la articulación de la rodilla. Los datos pueden ser útiles para los especialistas que trabajan en el campo de la implantología y el desarrollo de sistemas de prótesis de cadera.

Palabras clave: Osteoartritis; Meseta tibial; Prótesis; Carga.

INTRODUCTION

Hip arthroplasty is a common and successful surgical procedure designed to restore limb function and improve the quality of life for patients suffering from osteoarthritis and other degenerative hip joint diseases.

⁽¹⁾ About one million hip arthroplasty operations are performed annually worldwide, with 95 % of implants surviving 10 years and 80 % - 25 years. ⁽²⁾ In Ukraine, about 25 thousand patients require hip arthroplasty every year, but only 7-10 thousand receive assistance per year. Modern methods of hip arthroplasty include cement-free implant technology, minimally invasive surgical methods, computer navigation, and more modern and safe materials. ⁽³⁾

Negative changes in large joints, especially knee joints, are common, so modelling considering mechanical changes can reduce extraneous effects. The optimal position of endoprosthesis components, particularly the center of rotation, is crucial for hip arthroplasty. An incorrect position of the prosthetic head may result in dislocation of the hip. ⁽⁴⁾ The cause of endoprosthetics is often severe dysplasia and other significant defects of the hip cavity, in which it is difficult to install the acetabular component of the prosthesis in an anatomical position, and degenerative and inflammatory diseases that change the shape of the joint surfaces. ⁽⁵⁾ Therefore, restoring the anatomical centre of rotation is often problematic. ⁽⁶⁾

Studies show that about 50 % of patients have a displacement of the hip rotation center within a few millimeters, making it important to predict how significant this displacement is and how it changes the redistribution of forces acting in the limb joint system. ⁽⁷⁻⁹⁾ The correct location of the rotation center affects the biomechanical conditions of functioning not only of the hip but also of other joints of the lower limb, particularly the knee. ^(10,11)

There is a need for a detailed study of the effect of changes in the center of rotation on the axis of the lower limb and the knee joint after hip arthroplasty. Among the modern methods that significantly expand the possibilities of prosthetics, modern methods of mathematical and 3D modelling should be distinguished, which allow predicting the results of the intervention. ^(12,13)

This study's purpose is to examine the impact of femoral head rotation changes on knee joint load after hip arthroplasty and to develop a mathematical model to determine load changes at different hip joint displacements. This research is crucial for orthopedic doctors to determine optimal prosthesis positions, predict complications, and select the best rehabilitation strategy.

METHODS

A mathematical model and 3D simulation model of the lower limb were created using Solidworks software suite, which included an arthroplasty of hip, femur, tibia, and tibial plateau cartilage, to analyze the impact of rotation center changes on knee joint. The load on the hip arthroplasty (on the centre of rotation) was the body weight acting on the lower limb, respectively shifting the centre of rotation 2, 4, 6, and 8 mm medially and laterally from the starting position. The patient's knee joint load was determined using solid body mechanics equations and anatomical features of the hip and knee joints while standing with uniform body weight distribution.

Mathematical model. The hypothetical weight of the patient included in the model was 90 kg. The force acting vertically down through the centre of rotation was calculated using equation $F_{total} = m \cdot g$ (1), where: F_{total} is the force acting on the knee joint from the weight of the body; m - patient's mass; g - gravitational force. According to the law of moments of forces for a system of rigid bodies $M = F \cdot d$ (2): where M - moment of force in the knee joint; F - force acting on the knee joint; d - distance from the centre of rotation of the hip joint to the knee joint.

Calculation of additional load: when the centre of rotation is shifted by Δx , the distance d changes by $d + \Delta x$. Therefore, the moment of force in the knee joint will be $M' = F \cdot (d + \Delta x)$ (3), where M' - moment of force when the centre of rotation changes; Δx - lateral displacement of the centre of rotation of the hip joint.

Difference in moments of forces before and after displacement of the centre of rotation: $\Delta M = M' - M$ (4),

where ΔM - difference in the moment of force in the knee joint during displacement.

Additional load on the lateral surface of the knee joint from displacement: $P = (\Delta M) / d$ (5), where P - additional load on the lateral and medial surface of the knee joint from displacement.

A parametric model was created, setting dimensional and anatomical parameters, and used to study the biomechanics of hip and knee joints. The main goal was to determine the load on the lateral and medial plateau of the tibia in the knee joint, when the centre of rotation of the hip joint changes after hip arthroplasty by 0, 2, 4, 6, 8 mm, medial and lateral to the initial data. Researchers used a geometric model to study the change in knee joint angle due to hip joint displacement. The lower limb consists of two rigid segments, and the upper segment moves with the hip joint shift. Using trigonometric functions, the change in angle can be determined: $\tan(\theta) = (\Delta x / d)$ (6) and $\theta = \arctan(\Delta x / d)$ (7), where: θ - change in the angle of the knee joint.

It was assumed that $d = 0,4$ m (this is the approximate distance from the hip joint to the knee for an adult). The load experiment was performed in the SolidWorks software suite using the SimulationXpress tool. Type of analysis: static, simulating standing on one leg.

RESULTS

As mentioned above, a change in the hip joint's center of rotation after complete endoprosthetics can lead to a change in the mechanics of the knee joint and a decrease in its stability. The force acting vertically down through the center of rotation was calculated at 882,9 N for a patient with a 90 kg weight. The patient's lower limb was modeled using SolidWorks software and SimulationXpress tool, examining the impact of two forces on the prosthesis head (figure 1).



Figure 1. Model of the lower limb with a prosthetic head of the hip joint, the force vectors acting on the prosthesis are indicated

The simulation process involved creating a geometric image and breaking it down into spatial elements, creating a grid. The program determined the dimensions of the elements based on volume, surface area, and geometric features. The model showed that shifting the hip joint center of rotation causes a change in hip angle, affecting the knee joint angle. This can lead to uneven load distribution, stressing the lateral and medial tibial condyles. Figure 2 shows the change in pressure in the knee joint in frontal and axial projections. The number indicates the area that receives the greatest pressure, and other colours indicate the surrounding areas where the load is distributed.

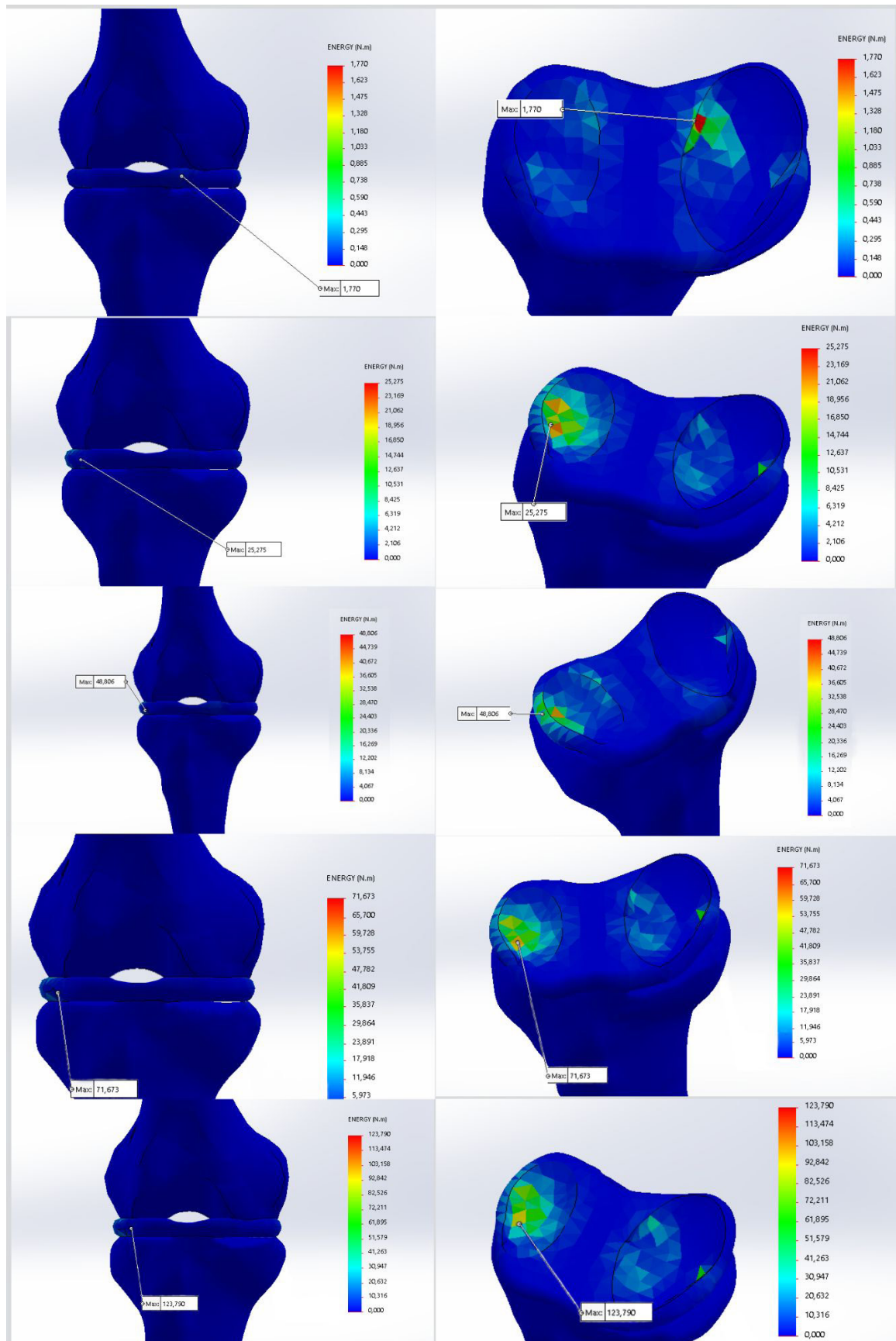


Figure 2. Model of the knee joint that reflects the load on the contact surfaces during medial displacement of the centre of rotation

The model reveals that the maximum pressure in the knee joint is 1,77 N·m in the anatomical position of the tibia's center of rotation. When displaced, this pressure can increase tenfold and move to other positions. The load redistribution leads to increased pressure on areas of the joint surface not physiologically affected. When the hip joint's center of rotation changes from zero, the angle of inclination changes, causing additional load on the knee joint's medial surface. The angle change is linear and proportional to the displacement of the center of rotation. The data is listed in table 1.

Table 1. Change of angle when the centre of rotation is shifted	
Rotation centre displacement, mm	Angle change, degrees
2	0,287
4	0,573
6	0,859
8	1,146

The angle of inclination of the femur can affect joint movement, muscle and ligament tension, limb length, and uneven pressure on other joints, including the knee. The force acting on the lateral surface of the knee joint increases significantly in proportion to the displacement of the centre of rotation (table 2). Changes in hip tilt affect hip adductor muscles activity, affecting gait biomechanics. This may affect lower limb kinetic parameters and joint pressure vectors, but this aspect is beyond the scope of this study. The shift change is quite significant and can have pronounced effects.

Table 2. Force acting on the lateral surface of the joint during medial displacement of the centre of rotation		
Rotation centre displacement, mm	Force acting on the lateral surface, N.m	Displacement force difference, N.m
0	1,77	0
2	25,275	23,505
4	48,806	46,836
6	71,673	69,903
8	123,79	122,02

Data on the maximum load on the surface of the knee joint during lateral displacement are shown in Table 3. Load growth is also linear. The table shows data on the additional load that occurs during displacement. As can be seen from Tables 2 and 3, the load on the tibial condyles increases tenfold, so changes in the knee must be considered when planning hip arthroplasty.

Table 3. Force acting on the medial surface of the joint during lateral displacement of the centre of rotation		
Rotation centre displacement, mm	Force acting on the lateral surface, N.m	Displacement force difference, N.m
0	1,77	0
2	21,735	19,965
4	44,033	42,263
6	69,975	68,205
8	120,25	118,48

The authors also calculated the change in additional load per millimetre in the medial and lateral directions. The calculation results are presented in table 4. It can be seen that the change in load on the lateral surface of the knee joint when the centre of rotation shifts from 0 to 6 mm is approximately the same and averages $11,65 \pm 1$ N/mm. However, when the centre of rotation is shifted from 6 to 8 mm, there is a significant increase in the load to 26,058 N/mm. A similar situation is observed with medial displacement. From the above data, it can be seen that with a displacement of more than 6 mm, the load on each mm increases by more than 2 times. These data deserve special attention, as such a bias may be critical from a clinical standpoint.

Table 4. Additional load on each mm that occurs when the centre of rotation is shifted, N·m

Displacement, mm	With lateral displacement of the centre of rotation	With medialisation of the rotation centre
from 0 to 2 mm	9,982	11,752
2 to 4 mm	11,149	11,765
4 to 6 mm	12,971	11,433
6 to 8 mm	25,137	26,058

Increased load on the tibial plateau may cause stress and pressure on knee joint structures so, a displacement of more than 6 mm can be critical for the functioning of the knee joint. The model suggests that altering the hip joint's rotation during implantation can significantly alter the pressure distribution on the lower limb and knee joint. Comparing simulation data with real-world scenarios is crucial for understanding joint interaction. In the *in vivo* situation, bones and joints are located in a system connected by the musculoskeletal system, the condition of which will also contribute to load distribution.

DISCUSSION

The study investigates the impact of changes in the center of rotation after hip arthroplasty on knee joint load, highlighting the importance of understanding biomechanical conditions. A study by Bjarnason and Reikeras⁽⁶⁾ found that 55 % of patients with total hip arthroplasty experience a change in the center of rotation, potentially leading to femoral displacement and reducing knee joint stability. When the centre of rotation is shifted medially from the normal position, the load on the lateral tibial condyle increases, which coincides with the results of the modelling in this study.

The redistribution of forces in the knee joint can lead to knee pain and osteoarthritis, as incorrect pressure distribution on the joint surface and subchondrial bones is a significant factor.⁽¹⁴⁻¹⁶⁾ *In vitro* study by Bourne et al.⁽¹⁶⁾ on cartilage tissue culture reveals that supraphysiological increases in hydrostatic pressure lead to changes in gene regulation, activating genes responsible for cellular respiration and suppressing processes like ossification, connective tissue development, and chondrocyte differentiation. This study explains the macro-level degenerative changes in cartilage tissue in response to prolonged pressure increases, particularly in the knee joint.

Studies show unequal displacement of the center of rotation, with medial displacement having less clinical effect and potentially reducing hip joint load on abductor muscles, but understanding these changes' impact on the knee joint is crucial.^(7;18,19) In a survey of 110 hip arthroplasty patients, Nieschk et al.⁽²⁰⁾ found that displacement of the center of rotation worsens mobility indicators, particularly the Barthel Index, and increases pain. The best indicators for all the studied parameters were provided by the exact anatomical location of the centre of rotation, thus confirming the need to preserve the centre of rotation as accurately as possible. Lerner et al.⁽²¹⁾ study on musculoskeletal models found that deviation from tibia and femur alignment changes the peak contact force of the medial division by 51 N, and medial-lateral displacement of contact points by 41 N.

It is important to note that the results of this study are based on a mathematical model that, although tries to reproduce real biomechanical processes, still has its limitations. Additional experimental studies may be needed to confirm these results in a real-world clinical setting. It is also worth considering that other factors, such as the patient's age, the condition of muscles and tendons, and other anatomical features, can affect the actual load on the knee joint after hip arthroplasty.⁽²²⁾ It should also be noted that the likelihood of complications is additionally due to changes in the overall biomechanics of the musculoskeletal system and forced posture, which may have occurred in the patient as an adaptation to the painful condition in the preoperative period.⁽²³⁻²⁵⁾ Abolghasemian et al.⁽²⁶⁾ found that post-total arthroplasty, the joint's rotation center shifts by 23,4 % and down by 20,8 %, causing a decrease in joint response and weakening hip muscle strength. This change may affect knee joint function in other kinetic positions.

Rajpura et al.⁽²⁷⁾ found 33 hip arthroplasty patients experienced an average 7mm displacement of the prosthesis head, altering muscle forces and bone tilt, potentially disrupting other joints. The consequence of this can be a change in the vectors of muscle forces and bone tilt, which also disrupts the work of other joints. Van Drongelen et al.'s⁽²⁸⁾ study reveals hip-knee joint changes after hip arthroplasty, with increased contact between femur and tibia, leading to 39 % increased pressure on the knee joint, suggesting the need for a musculoskeletal model.

The prevalence and clinical consequences of this pathology necessitate the identification of potential surgical causes of displacement and their reduction.⁽²⁹⁾ Benson et al.⁽³⁰⁾ study on 894 endoprosthetic patients revealed that the type of operational access significantly impacts the displacement of the hip rotation center. This displacement can have significant clinical consequences, so it is important to consider such aspects when

planning surgery. Messer-Hannemann et al.⁽³¹⁾ study highlights the importance of acetabular reaming and grinding in hip cup implantation to restore the prosthesis's anatomical position and balance it with a healthy leg, addressing factors like dysplasia and deformity.

Marsh and Newman's⁽³²⁾ review highlights the effectiveness of individualisation in hip and knee replacement, increasing implant survival rates to 98,2 % and 96,6 % after 20 years. This reduces complications like dislocation, loosening, and infection, and reduces revision surgery frequency. Computerisation of modelling and manufacturing expands implant use, but technical and economic factors hinder their spread. 3D modelling helps study knee joint biomechanics and joint relationships.⁽³³⁾

CONCLUSIONS

This paper presents the development of a model of a human lower limb in SolidWorks software suite using the SimulationXpress tool to simulate standing on one leg. The study highlights the critical importance of understanding how changes in the center of rotation after hip arthroplasty impact the load distribution in the knee joint. Despite hip arthroplasty's high success rate in restoring limb function and quality of life for patients with osteoarthritis and other degenerative hip diseases, it can lead to biomechanical changes in other joints, particularly the knee.

Lateral displacement of the center of rotation increases the load on the medial tibial condyle, while medial displacement increases the load on the lateral tibial condyle. Such changes can exacerbate knee pain and contribute to the development of osteoarthritis. The findings indicate that even minor shifts in the hip's center of rotation can lead to significant changes in knee joint biomechanics, potentially resulting in uneven load distribution and increased pressure on non-physiological areas. This can cause degenerative changes and affect overall joint stability. It is crucial for orthopedic surgeons to consider the implications of hip rotation center displacement during arthroplasty. Accurate positioning of the prosthesis is essential to minimize adverse effects on the knee joint. The study underscores the value of advanced modeling techniques in predicting these outcomes and guiding surgical planning.

Future research should validate the model by comparing simulation results with real-world clinical data, explore post-arthroplasty hip-knee joint interaction, and investigate patient-specific factors like age, muscle condition, and preoperative biomechanics to improve surgical outcomes.

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