Lek. Maciej Waldemar Kostewicz

Biomechaniczne uwarunkowania predysponujące do zwichnięcia stawu biodrowego po alloplastyce.

Rozprawa na stopień doktora nauk medycznych i nauk o zdrowiu
w dyscyplinie nauki medyczne
Warszawskiego Uniwersytetu Medycznego

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Spis treści

Rozdział 1.

Wykaz zastosowanych skrótów:

THA- Total hip arthroplasty- całkowita alloplastyka stawu biodrowego

SF - Safety Factor- współczynnik bezpieczeństwa

FEM- Finite element method- metoda elementów skończonych

CT- Computer tomography- tomografia komputerowa

N- Newtons – niutony (jednostka siły w układzie SI)

Rozdział 2.

Streszczenie w języku polskim

Całkowita alloplastyka stawu biodrowego (THA) stanowi skuteczne i powszechnie stosowane leczenie zaawansowanej choroby zwyrodnieniowej stawu biodrowego. Pomimo doskonałych wyników klinicznych jednym z najpoważniejszych powikłań pozostaje zwichnięcie endoprotezy, którego częstość najczęściej nie przekracza 1-3 %, choć w grupach chorych wysokiego ryzyka może osiągać nawet 10–25%. Jego główną przyczyną są nieprawidłowości techniczne osadzenia elementów składowych protezy oraz współistniejące czynniki kliniczne zaburzające równowagę biomechaniczną sił oddziałujących na staw biodrowy.

Celem mojej pracy była ocena wpływu sposobu osadzenia panewki i trzpienia endoprotezy na stopień ryzyka zwichnięcia protezy. Badania przeprowadziłem in vitro z wykorzystaniem numerycznego modelowania biomechanicznego opartego o metodę elementów skończonych (FEM). Na podstawie trójwymiarowego modelu miednicy, opracowanego na bazie

przykładowej tomografii komputerowej osoby zdrowej, przeprowadziłem symulacje dla różnych konfiguracji osadzenia panewki i trzpienia protezy zmieniając kąt inklinacji i antewersji panewki, głębokość osadzenia trzpienia oraz offset głowy protezy. Obciążenia mechaniczne protezy odpowiadały warunkom podporu jednonożnego ciężarem ciała, a dodatkowo oddziałujące na implant wartości sił mięśniowych oddziałujących na staw ustalałem na podstawie danych literaturowych.

Uzyskane wyniki wykazały, że jedynie konfiguracja uznana za optymalną w wyniku trwających już ponad osiem dekad obserwacji i doświadczeń klinicznych (panewka osadzona przy 45° inklinacji i 15° antewersji; ze standardowym offsetem; przy prawidłowej głębokości posadowienia trzpienia) zapewnia biomechaniczną równowagę sił oddziałujących na zaprotezowany staw, co znalazło potwierdzenie w wysokich wartościach współczynnika bezpieczeństwa (SF) rzędu 9–12. W odbiegających od tej konfiguracji modyfikacjach osadzenia elementów protezy stwierdzono znaczące zmniejszenie wartości SF do wartości 2–5, szczególnie w przednio-górnym i tylno-górnym kwadrancie panewki, wskazując na zwiększone w tych obszarach ryzyko zwichnięcia.

Wyniki te potwierdzają dotychczasowe obserwacje kliniczne. Wskazują one na rolę sposobu osadzenia elementów protezy stawu biodrowego w jej zwichnięciach przy wystąpieniu dodatkowych czynników wywołujących, jakimi mogą być dodatkowe urazy mechaniczne doznawane przez chorego pojawiające się podczas wykonywania niezamierzonych ruchów i zdarzeń losowych (upadek ze schodów, potracenie przez samochód, napad padaczki) oraz predyspozycji chorego (zwiększona ante- lub retrowersja miednicy, atrofia mięśniowa, zastosowany dostęp chirurgiczny — tj. jatrogenne uszkodzenie przyczepów mięśniowych).

Przeprowadzone badania potwierdzają, że metoda elementów skończonych jest wartościowym narzędziem służącym do prognozowania biomechanicznej stabilności endoprotezy stawu biodrowego. Uzyskane wyniki mają znaczenie praktyczne i mogą być wykorzystywane do optymalizacji techniki operacyjnej, doboru komponentów oraz zastosowania technologii wspomagających (nawigacji komputerowej, robotyki) w celu jak najbardziej precyzyjnego osadzenia implantów, co minimalizuje ryzyko zwichnięcia.

Streszczenie w języku angielskim

Biomechanical conditions predisposing to hip dislocation after arthroplasty.

Total hip arthroplasty (THA) is an effective and widely used treatment for advanced osteoarthritis of the hip joint. Despite excellent clinical outcomes, prosthetic dislocation remains one of the most serious complications, with an incidence reaching up to 10–25% in high-risk patient groups. The main causes of hip joint instability after THA are technical inaccuracies in the placement of prosthetic components within the bony sockets, as well as coexisting clinical factors affecting the biomechanical balance of the hip joint.

The aim of this dissertation is to evaluate the influence of acetabular cup and femoral stem placement on the level of prosthetic dislocation risk. The study was carried out as a computational study using numerical

biomechanical modeling based on the finite element method (FEM). Based on a three-dimensional pelvic model developed from computed tomography of a healthy individual, simulations were performed for various configurations of acetabular cup and femoral stem placement by modifying cup inclination and anteversion angles, femoral stem insertion depth, and femoral head offset. Mechanical loads applied to the prosthesis corresponded to single-leg stance body weight, and additional muscle forces acting on the implant were determined based on literature data.

The obtained results showed that only the configuration considered optimal as a result of over eight decades of observations and clinical experience (cup: 45° inclination, 15° anteversion; standard offset; correct stem depth) provides biomechanical equilibrium of forces acting on the prosthetic joint, which was confirmed by high safety factor (SF) values of 9–12. In configurations deviating from this placement of prosthetic components, a significant decrease in SF values to the level of 2–5 was observed, particularly in the anterosuperior and posterosuperior quadrants of the acetabulum, indicating an increased risk of dislocation. The obtained results confirmed previous clinical observations.

They indicate the role of prosthetic component placement in hip joint dislocations when additional triggering factors occur, such as trauma sustained by the patient, unintended limb movements (falling down stairs, being hit by a car, epileptic seizure), and patient predispositions (such as excessive pelvic tilt, muscle atrophy, surgical approach—i.e., iatrogenic detachment of muscle attachments, etc.), confirming the conclusions of previous observations that the configuration considered most favorable minimizes the risk of subsequent implant dislocation in the presence of additional predisposing factors.

The conducted study confirms that the finite element method is a valuable tool for predicting biomechanical stability of hip prostheses. The obtained results are of practical importance and may be used to optimize surgical techniques, component selection, and the use of supportive technologies (computer navigation, robotics) to minimize the risk of dislocation. They also indicate the necessity of individualized treatment and consideration of the full clinical context in surgical planning.

Based on the literature review, it was indicated that prosthetic instability may be influenced by, among others, neurological, anatomical, and surgical factors, as well as noncompliance with postoperative recommendations.

Rozdział 3.

Wstęp uzasadniający połączenie wskazanych publikacji w jeden cykl, jak i komentujący osiągniecie naukowe kandydata na tle dotychczasowego stanu wiedzy.

Całkowita alloplastyka stawu biodrowego (THA – *Total Hip Arthroplasty*) jest obecnie jedną z najczęściej wykonywanych procedur ortopedycznych na świecie. Wskazania do zabiegu obejmują głównie zaawansowane zmiany zwyrodnieniowe stawu biodrowego, jałową martwicę głowy kości udowej, deformacje pourazowe, zmiany nowotworowe. Postęp w technologii materiałów, konstrukcji implantów oraz technik operacyjnych doprowadził do istotnego wzrostu skuteczności leczenia oraz skrócenia czasu rekonwalescencji.

Zwichnięcie endoprotezy stawu biodrowego to utrata kontaktu głowy endoprotezy z panewką wynikająca z zaburzenia równowagi sił działających w obrębie obręczy biodrowej. Do zdarzenia tego dochodzi zwykle wskutek niekorzystnej pozycji kończyny dolnej połączonej z nadmiernym lub niekontrolowanym działaniem sił zewnętrznych i wewnętrznych (m.in. napięć mięśniowych), szczególnie w sytuacji, gdy komponenty protezy zostały nieoptymalnie osadzone. W literaturze przedmiotu częstość zwichnięcia po pierwotnej alloplastyce ocenia się na 1,4 - 5%, natomiast w grupach ryzyka – m.in. po operacjach rewizyjnych, u chorych ze schorzeniami układu nerwowego powodującymi zaburzenia równowagi i napięcia mięśniowego, z ograniczeniem ruchomości kręgosłupa, z zaburzeniami poznawczymi lub po urazach ryzyko to może wzrosnąć do nawet 25%.

Dane literaturowe wskazują, że zdefiniowane przez Lewinneka kąty ustawienia panewki – tj. inklinacja 40° ± 10° i antewersja 15° ± 10° – choć powszechnie stosowane w praktyce klinicznej, nie gwarantują optymalnej stabilności implantu i nie są wystarczające do zapobiegania zwichnięciom u chorych z nieprawidłową biomechaniką miednicy lub współistniejącymi zaburzeniami funkcjonalnymi. Czynniki takie jak mobilność miednicy i kręgosłupa, napięcie mięśniowe, długość kończyn, offset głowy protezy czy nawet wzorce ruchowe pacjenta podkreślają konieczność indywidualizacji strategii implantacyjnej oraz dokładnego zrozumienia wpływu tych parametrów na funkcjonowanie i stabilność endoprotezy stawu biodrowego.

W niniejszej rozprawie podjąłem próbę stworzenia cyklu publikacji, który ma charakter zarówno poznawczy, jak i praktyczny, łącząc analizę przeglądową z badaniami biomechanicznymi opartymi na komputerowej symulacji rzeczywistych warunków obciążeniowych. Cykl składa się z dwóch publikacji:

- Pierwsza praca (Kostewicz M. i wsp., *Medical Science Monitor*, 2022) ma charakter narracyjnego przeglądu aktualnego stanu wiedzy dotyczącego mechanizmów zwichnięcia protez stawu biodrowego oraz czynników ryzyka. Szczególny nacisk położono na zależność między ustawieniem komponentów endoprotezy a stabilnością stawu, rolę struktur mięśniowo-więzadłowych, wpływ patologii współistniejących (w tym neurologicznych i kręgosłupowych) oraz czynniki behawioralne i demograficzne. W publikacji wskazano na znaczącą lukę w zakresie jednoznacznej, ilościowej oceny biomechanicznej skutków nieoptymalnego ustawienia komponentów – co stało się bezpośrednim impulsem do przeprowadzenia dalszych badań.

- Druga publikacja (Kostewicz M. i wsp., *Journal of Clinical Medicne* 2025) stanowi oryginalne badanie biomechaniczne, w którym opracowano realistyczny trójwymiarowy model miednicy z osadzoną endoprotezą stawu biodrowego i przeprowadzono symulacje komputerowe z wykorzystaniem metody elementów skończonych (FEM). Analiza objęła warianty zmiennego ustawienia panewki i trzpienia (w zakresie kąta inklinacji, antewersji, głębokości osadzenia trzpienia i offsetu głowy). Wykazano, że jedynie implantacja zgodna z anatomicznymi parametrami referencyjnymi (nachylenie 45°, antewersja 15°, prawidłowy offset) zapewniała biomechaniczną równowagę sił i wysokie wartości współczynnika bezpieczeństwa (SF = 9–12). Odchylenia od tych parametrów prowadziły do istotnego spadku SF (do 2–5), zwłaszcza w newralgicznych obszarach panewki, odpowiadających klinicznie typowym lokalizacjom zwichnięcia.

Połączenie tych dwóch opracowań w jeden cykl pracy doktorskiej jest w pełni uzasadnione zarówno pod względem tematycznym, jak i metodologicznym. Obydwie publikacje wzajemnie się uzupełniają: pierwsza przedstawia szeroki kontekst kliniczny i patofizjologiczny, druga dostarcza obiektywnych danych ilościowych z zakresu biomechaniki. Razem tworzą spójną strukturę naukową, umożliwiającą nie tylko pogłębione zrozumienie mechanizmów zwichnięcia, ale również wskazanie konkretnych rozwiązań mogących wpłynąć na poprawę bezpieczeństwa i skuteczności leczenia operacyjnego.

Prezentowane w rozprawie wyniki badań należy zakwalifikować jako oryginalne oraz istotne z perspektywy rozwoju wiedzy w dziedzinie ortopedii rekonstrukcyjnej i inżynierii biomedycznej. Zastosowanie nowoczesnych narzędzi badawczych w ocenie wpływu ustawienia komponentów endoprotezy stawu biodrowego na jej stabilność stanowi ważny krok w kierunku leczenia ortopedycznego. Wyniki mogą mieć bezpośrednie zastosowanie w planowaniu przedoperacyjnym, doborze typu implantu oraz w rozwoju technologii wspomagających implantację (np. nawigacja komputerowa, chirurgia robotyczna).

Rozdział 4.

Założenia i cel pracy

Cel pracy doktorskiej

Celem niniejszej rozprawy doktorskiej jest ocena biomechanicznego wpływu różnych konfiguracji ustawienia elementów endoprotezy stawu biodrowego (panewki i trzpienia) na ryzyko jej zwichnięcia, z wykorzystaniem modelowania numerycznego w oparciu o metodę elementów skończonych (FEM), oraz zestawienie wyników symulacji z aktualnym stanem wiedzy klinicznej dotyczącym przyczyn i czynników ryzyka destabilizacji protezy.

Założenia szczegółowe pracy

1. Opracowanie trójwymiarowego modelu biomechanicznego miednicy i stawu biodrowego z osadzoną endoprotezą**,** w oparciu o dane obrazowe (CT) oraz rzeczywiste warunki obciążeniowe występujące w trakcie podporu jednonożnego.
2. Przeprowadzenie symulacji komputerowych (FEM) dla różnych wariantów ustawienia implantów (w zakresie kąta inklinacji, antewersji panewki, offsetu głowy oraz głębokości osadzenia trzpienia).
3. Ocena wartości współczynnika bezpieczeństwa (SF) w poszczególnych konfiguracjach i identyfikacja stref największego przeciążenia jako potencjalnych miejsc predysponujących do zwichnięcia.
4. Zestawienie wyników biomechanicznych z przeglądem czynników klinicznych i anatomicznych opisywanych w literaturze jako zwiększających ryzyko destabilizacji endoprotezy.
5. Sformułowanie zaleceń praktycznych dla chirurgów ortopedów dotyczących optymalnego ustawienia komponentów protezy w zależności od indywidualnych warunków pacjenta (morfologia, biomechanika miednicy, współistniejące patologie).

Rozdział 5.

"Narrative Review of the Mechanism of Hip Prosthesis Dislocation and Methods to Reduce the Risk of Dislocation."

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Narrative Review of the Mechanism of Hip Prosthesis Dislocation and Methods to Reduce the Risk of Dislocation

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Data Collection B
Statistical Analysis C
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Manuscript Preparation E
Literature Search F
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Total hip arthroplasty (THA) is one of the most effective surgical procedures. It improves quality of life, increases range of motion, and reduces pain in patients with hip joint degeneration. THA allows patients to return to everyday social and professional activities. Therefore, today it is the best approach to treatment of several chronic conditions affecting the hip joint, including advanced degenerative diseases, avascular necrosis, and some traumatic events. The aim of this study was to present the mechanism of hip prosthesis dislocation, associated risk factors, and the factors reducing the risk of dislocation, as well as its consequences and methods of risk minimization.

Hip dislocation is a common complication following THA. It is responsible for up to 2% to 3% failures of primary replacements, increasing even to 10% in extreme cases of patients highly predisposed to this condition. In most cases, technical errors during implant placement are responsible for the incidence. The measures taken to prevent complications include activities aimed at correct implant insertion and the selection of the most appropriate type of implant for the patient, depending on individual needs.

We summarized the current knowledge of implant dislocation to help surgeons understand the changes in biomechanics of the hip after its replacement and the impact of each particular element that participates in it. This knowledge can enable a surgeon choose the most favorable surgical method and the most appropriate implant to reduce the risk of implant dislocation.

Keywords: **Arthroplasty, Replacement, Hip • Hip Dislocation • Hip Joint • Hip Prosthesis**

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Background

Total hip arthroplasty (THA) is one of the most effective orthopedic procedures. It relieves pain, restores joint mobility, and improves patient quality of life. It allows patients to return to their everyday social and professional activities. Consequently, today it is the best approach to treat several chronic conditions affecting the hip, including advanced degenerative diseases, avascular necrosis, and some traumatic events [1].

Nevertheless, despite the various unquestionable benefits, THA is not free from complications, with dislocation being among the most frequent, responsible for 1.4% to 5.0% of primary THA. Although much effort has been devoted to dislocation prevention, the percentage of dislocations that leads to adverse sequelae after revision procedures is even higher, reaching up to 25% [2].

Dislocation, whose problem lies within the loss of contact between the prosthetic head and its acetabulum, is due to an extreme position of the joint caused by the impact of excessive mechanical forces on the involved lower limb. It can occur with or without implant loosening, periprosthetic fractures, and infection [1].

The aim of the paper was to summarize the mechanism of hip endoprosthesis dislocation, the risk factors, and the factors preventing it, as well as its consequences and methods of risk minimization.

Mechanisms of Dislocation

Dislocation occurs when forces acting over the implant in a detrimental direction reach amplitudes that overcome those keeping it intact. It usually takes place as a consequence of unintended external forces that act on a limb placed in an unfavorable position. However, it can also be due to excessive, uncoordinated muscle contractions, such as during epileptic seizures [2,3]. Anatomically, the durability of the articular capsule, which is strengthened by several ligaments, namely the iliofemoral, pubofemoral, and ischiofemoral ligaments, and that of the head of the femur, prevent joint dislocation. After arthroplasty, the postoperative scar formed around the joint partly takes over the function of these ligaments. The scar is supported by negative pressure in the joint cavity, imposing suction force of the value proportional to the contact surface between adherent parts of the prosthesis, and the net force of muscles acting on the pelvic girdle that protects implant integrity (**Figure 1A, 1B**). The implant is far more prone to dislocation than the anatomical hip owing to the deficiency of the femoral head ligament and the far lower durability of the scar than of the joint capsule and the ligaments supporting it. It is especially prone to dislocation shortly after the procedure, when maturation of the scar is not complete [4].

The amplitude of the net force that stabilizes the hip is highest when its vector is parallel to the acetabular axis. Under such conditions, it presses the prosthetic head toward the acetabulum, protecting it from dislocation. However, when it acts at the same angle, it distributes 2 component forces: the first acting parallel, and the second acting perpendicular to it. The first force presses the head against the acetabulum, supporting its stability, whereas the second force promotes dislocation. The amplitude of the second force is proportional to the sine value of this angle.

Anatomical distribution of the femoral muscles indicates that standing on both legs with the thighs abducted and internally rotated generates net force, which acts almost approximately on the acetabular axis, in both the frontal and the sagittal planes. Thus, in this position, dislocation of the prosthesis is unlikely. However, when the hip is flexed and externally rotated, its distal attachments move anteriorly, changing the direction of their vectors. Consequently, the vector of the net force runs obliquely, generating component force that promotes dislocation. Several routinely performed everyday activities involve limb adjustment in positions that provoke dislocation, including forbidden ones. These include sitting in a cross-legged position, deep squats with heels down, high amplitude swings, and external rotations of maximally abducted and flexed hips. Inappropriate alignment of an artificial prosthetic acetabulum, namely inclination above 70°, retroversion, and too deep positioning, relocates its axis, leading to generation of the component force that dislocates the implant. Therefore, even a relatively small muscular contraction can result in dislocation. Additionally, in those cases, skew distribution of forces acting on the acetabulum contributes to faster loosening and tear-off and fragmentation of its polyethylene insert [2].

Positioning of the Acetabulum

Inappropriate positioning of the acetabulum is the most frequent iatrogenic causative factor of dislocation [5-7]. Based on decade-long observations, the parameters of the optimal positioning of the acetabulum have been defined. They include 45±5° inclination, 15±10° anteversion, and restoring anatomical axis of the joint by its proper location in terms of depth and height [7]. Deviation by more than 3 mm in height and medialization above 5 mm result in asymmetric distribution of mechanical loads, contributing to dislocation [8]. Thus, too steep (inclination above 70°) positioning of the acetabulum with too high (above 30°) or too small (less than 10°) anteversion are recognized as the causative factors of dislocation; especially, when they are associated with its excessive medialization [9].

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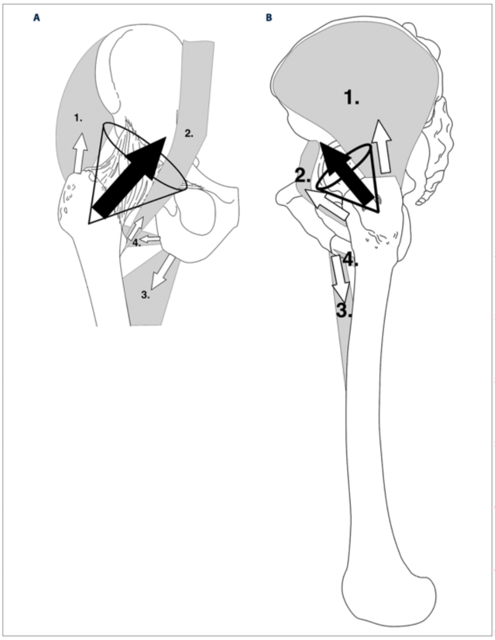

Figure 1. (**A, B**) Schematic presentation of the net force of the main muscle groups (gluteal (**1**), iliopsoas (**2**), adductors (**3**) and represented together piriformis, quadrature femoris, both obturatory and both gemmeli (**4**)) acting over the proximal femur. Anteroposterior (**A**) and lateral (**B**) views.

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Kostewicz M. et al.
Hip prosthesis dislocation
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It is noteworthy that attentiveness to the recommended parameters reduced the incidence of dislocations, loosening of the acetabulum, and acetabular displacement. Therefore, they are generally accepted and widely applied. However, despite their unquestionable usefulness, they do not exclude the risk of dislocation owing to the negative impact of other factors.

Muscular Disorders Favoring Dislocations

Muscular imbalance due to muscle dysfunction or inappropriate coordination of the muscle groups affecting the hip results in inappropriate mechanical loads exerted on the prosthesis. Muscular imbalance can be due to changes in muscle length, such as elongation or shortening, as a consequence of altered anatomical positions of muscular attachments, or by muscles being stretched or relaxed, which leads to their relative mechanical insufficiency. Surgical release of muscular attachments can result in their absolute insufficiency, if not healed. Muscular fibrosis and denervation can also impair their function, usually because of excessively brutal or inappropriate surgical techniques [10,11].

Several analyses revealed that the posterior approach to hip replacement requiring release of external rotators and the posterior aspect of joint capsule increases the risk of dislocation in comparison to lateral, anterolateral, and anterior approaches. The meta-analysis comparing over 13 000 primary hip arthroplasties showed that dislocations complicate 3.23% of procedures performed using the posterior approach, but only 0.55% and 2.18% of those performed using the lateral and anterolateral approaches, respectively. Nevertheless, the percentage of dislocations can be decreased to 0.7% after anatomical reconstruction of the posterior joint capsule and external rotators [12]. In several studies, postoperative reconstruction of the joint capsule reduced the number of dislocations by almost 90% [13,14]. The lateral approach leads to an increased risk of functional weakening of abductors owing to partial detachment of the medial gluteal muscle and the greater trochanter, being responsible for 36% of postoperative dislocations [15]. It has been established that dislocation of the greater trochanter above 1 cm is connected with a 6-fold increased risk in prosthesis dislocation [16].

Inappropriate Positioning of the Stem

In most cases, inappropriate positioning of the stem leads to an excessive anteversion, too deep placement, or varus deformity [10,17]. Excessive anteversion draws back the axis of the prosthetic neck from the acetabular axis, while a too deep placement weakens the muscles whose proximal and distal attachments converge, and varus deformity can lead to the conflict between the medial aspect of the remaining femoral neck and the lesser trochanter with ischial tuberosity which, forming a 2-sided lever, can dislocate the prosthesis in a forcedly adducted and internally rotated limb.

It has been established that the lowest risk of dislocation occurs when the stem is positioned in 10° to 15° anteversion and at an appropriate depth to support it on the Adam's arch and to restore the calve line [18]. Inappropriate anteversion results in conflict between the stem and the cup and between bony prominences of the pelvis and femur, provoking conflicts that disrupt the balance between elements of the prosthesis and aggravating the risk of its dislocation and loosing. It is far more important in non-cemented prostheses, since the fixation of their acetabula pivots much more on the balance of forces that press it directly into its pelvic lodge. It has been noticed that the anteversion of the stem has to correspond with the anteversion of the acetabulum, summarized by the term "combined anteversion" [19]. This combined anteversion has been primarily assessed with values varying between 25° and 35° in men and up to 45° in women [20], and is currently qualified as 25° to 45° (mean 35°). The easiest way to implant a prosthesis according to those requirements is to implant primarily the stem with required anteversion, compensating the combined anteversion by strictly defined positioning of the acetabulum with computer navigation [21]. Implant setting also entails the risk of complications. Cemented stems have twice the lower risk of periprosthetic fractures than cementless ones [22].

Impact of Stiffness of the Lumbar Spine

A limited range of motion of the lumbosacral spine enforces increased compensatory overloads of the hip, thus being one of the risk factors for endoprosthesis dislocation. A limited range of pelvic tilt during typical everyday activities, including those requiring flexion and extension of the hip (sitting on the chair, standing), reinforces a compensatory range of motion in the prosthesis, which can contribute to its dislocation. Thus, hip arthroplasties performed in patients with ankylosing spondylitis have an extremely high risk of dislocation and loosening of the prosthesis in comparison to those in patients with osteoarthritis [23,24].

One study conducted in a sample of 1000 patients 1 year after primary THA showed that the patients who sustained dislocations had a substantially decreased range of motion in the lumbar spine and sacral slope, while, during standing and sitting, the differences between the involved and the uninvolved lower limb were significantly lower. The results indicated that 92% of patients with dislocations previously underwent surgeries of the lumbar spine, including spine fusions [25]. Analogous results have been obtained from the analysis of the biomechanical reasons for late prosthetic dislocations, in which the study found that the decrease of sacral tilt while changing the body position from standing to sitting forces a decrease in the range of hip motion by 0.9° per each 1.0° of limited spine mobility. The above findings explain the mechanism of late dislocations in patients with decreased spine mobility.

Pelvic retroversion predisposes patients to anterior dislocations, forcing hyperextension of the hip, while standing and anteversion predisposes to posterior dislocations due to excessive flexion in the sitting position [26]. It has been assessed that spondylodesis is the greatest independent risk factor for dislocations of hip prostheses during the first 6 months after arthroplasty [27].

Patient-Dependent Factors that Predispose to THA Dislocation

The patient-dependent factors that predispose patients to dislocation are shown in **Table 1**. Secondary injuries due to patient noncompliance with postoperative recommendations markedly increase the risk of dislocations. This is especially common in the early postoperative period, when an immature scar provides weak mechanical support of joint congruence. Dislocation can occur from leg crossing, squatting, and even performing movements in an excessive range of motion. During the first 3 months after surgery, inordinate movements increase the risk of dislocation owing to insufficient scar resistance [28]. However, an excessive scar formed around the joint can contribute to dislocation, levering the prosthetic's head from the acetabulum during contracture of muscles adjacent to the trochanteric area. This usually occurs in cases of repeated surgical interventions. Thus, revision procedures have a significantly higher risk of dislocations, reaching up to 28% of performed procedures. It is most prominent in wide tissue injuries, both traumatic and iatrogenic, that heal leaving an excessive scar and heterotopic ossification [29]. Deficits of skeletal tissues of the acetabulum and the proximal end of the femur form another group of risk factors for displacement [10].

In such cases, education of patients focused on elimination of movements leading to dislocation, carried out by an experienced physiotherapist, can reduce the risk of complication.

Dislocations can also occur in late periods after arthroplasty. Unfortunate events, such as falls, stumbling, and even car accidents, can result in dislocations and associated soft-tissue injuries [30]. Locomotor disability, including stiffness of

Table 1. Summary of patient-dependent factors that predispose to implant dislocation.

Numbers\the section	Patients-dependent factors that predispose to THA dislocation
1.	Insubordinate, alcohol, drug abused – corresponds with brawls
2.	Patients with neurologic and psychiatric disorders, including epilepsy, dementia, disorientation, ataxia, impaired consciousness, coma and delusions. Also - paresis and nerve palsy affecting the lower limb that impairs muscular balance of the pelvic girdle
3.	Undertaking professional risky activities that promote injuries to the hip joint: a. Stuntmen's b. Professional sportsmen's c. Soldiers, policemen's
4.	Very active amateur sportsmen a. Skiing b. Horse riding c. Football players d. Squash players e. Parachuting
5.	Bedridden patients that have an advanced muscular atrophy due to persistent disuse (lack of congruency of the hip joint)
6.	Lumbosacral pathology
7.	THA with low-diameter femoral head
8.	Technical errors in THA – inexperienced surgeon
9.	Advanced age (includes several of the factors mentioned above)
10.	Obesity (BMI >30 kg/m^2)

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the adjacent joints of the affected limb, contractures, and impairments of the visual and vestibular systems, hearing, and proprioception, increase the incidence risk [31]. Other factors include neurologic (paresis and cerebral palsy, Parkinson disease, myasthenia), metabolic (diabetes, hypoglycemia), cardiologic (stroke, arrhythmia, cardiac arrest) and many other disorders that predispose a patient to secondary injuries [32-34]. Patients with neuromuscular disorders are prone to dislocations due to an imbalance of particular groups of muscles, especially flexors and pronators. Additional risk factors for these patients include cognitive disorders, weakened muscle strength, impaired coordination and balance, and lack of the possibility to control the patient's activity that may culminate in dislocation of the prosthesis [5,35,36].

A very specific group of patients predisposed to dislocations includes vigorously physically active individuals, who do sport and undertake risky activities. The generation of much higher loads increases prosthesis wear, implant loss, and the risk of dislocation. Nevertheless, an appropriate selection of an implant that would be adequate for this particular group (low-friction working elements, head diameter 32 mm) and patient education eliminates the risk of this complication to the value of that in patients with low activity [37].

The unpredictable and often also irrational behavior of alcohol and drug abusers and mentally ill patients increases the risk of implant dislocation and periprosthetic fractures [37,38]. In those groups, both complications are the most frequent reasons for revision procedures [3,39]. Very strict preoperative planning, precise implant positioning, and careful postoperative care combined with an intensive rehabilitation program and education allow patients to reduce the risk of dislocations to an accepted level [40].

Patients with soft-tissue imbalance, joint deformities around the hips, and bilateral pathological hips seem to be more predisposed to implant dislocation. Recently identified risk factors include preoperative hip adduction deformity combined with limb lengthening of 2 cm postoperatively, knee valgus combined with pelvic obliquity deformity, and bilateral pathology of the hip that require arthroplasty. If the procedure is planned carefully and has proper postoperative management, dislocation after THA can be prevented [41].

Patients with Crowe type IV developmental dysplasia of the hip are at a high risk of dislocation after THA. Nevertheless, in those cases, implantations of an implant with higher size of the femoral head (28 instead of 22 mm) reduces the risk of dislocation. Risk can be lowered by improvement of the strength of the abductors in properly planned preoperative and postoperative rehabilitation [42].

Recently, obesity, especially morbid obesity, has been identified as one of the factors that increase the risk of dislocation. The relationship between body mass index (BMI) and the degree of THA instability, with a BMI of 40 kg/m^2 and higher, is noticeable. The circumference of the thigh, not the BMI itself, is a factor that directly reduces the stability of the joint. Moreover, the rate of THA dislocation in women with obesity is higher than that in men with obesity owing to the differences in fat deposition (women store fat mainly around the hips and thighs, whereas in men it is mostly distributed at the abdomen) [34,43].

Factors Preventing Hip Prosthesis Dislocation

Anatomically, the hip is protected from dislocation by active and passive stabilizers. Active stabilizers are the joint capsule and the pubofemoral, ischiofemoral, and iliofemoral ligaments supporting it. Additionally, the femoral head is powered by its own ligament and suction, which is the effect of negative pressure in the joint cavity during dislocation. Active stabilizers form muscles of the pelvic girdle [44,45]. Their net force presses the head of the prosthesis to its acetabulum, increasing congruency of the joint.

Surgical procedures deprive joints of some of the abovementioned elements. The surgical approach requires dissection, excision, and removal or release of the joint capsule and its ligaments and ligaments of the femoral head, and non-physiological limb movements overstretch muscles of the pelvic ring. The forthcoming fibrosis impairs their contractility, decreasing their strength [46,47]. Several recently introduced techniques preserve anatomical structures with a limited surgical intervention and reconstruction of joint capsule and muscle attachments [48,49]. However, the question of whether it is able to reduce the risk of complications is still controversial [50]. The range of iatrogenic lesions highly depends on the selected surgical approach, patient's constitution-related factors (obesity), previously performed interventions (scarring), and an excessive (even brutal) surgical technique. Unfortunately, even the most delicate, tissue-protecting technique does not guarantee preservation of anatomical structures. This especially concerns advanced stiffness of the hip, its wide scarring after previously performed procedures and injuries, and the question of when it is necessary to restore biomechanics in dysplastic high hip dislocations with the formation of the secondary acetabulum [51].

An inappropriate size of the prosthetic head can increase the risk of dislocation and accelerate the damage of its acetabulum. Unquestionably, heads with a greater diameter decrease the risk of dislocation, providing higher congruency. At the same time, however, they decrease the range of motion, jeopardizing implant levering in extreme joint positions [52].

Outcomes of Hip Prosthesis Dislocation

Dislocation leads to severe consequences. It can cause vast soft-tissue injury, including scar formation around the joint and the remainders of its capsule, muscles, and their attachments, contributing to bone fractures, the loss of bone, and the integrity and stability of the implant. When repositioned, deprivation of stabilizers can easily reoccur. The consequences of dislocation also include avulsion fractures, vast scarring, and heterotopic ossification [29,53].

Preoperative Planning

Careful preoperative planning, the use of the most suitable implant and surgical approach for the particular case, and an adequate postoperative rehabilitation program combined with education of patients play the most important role in prevention of dislocation.

Several meta-analyses determined that the most effective and least risky surgical approaches are suitable minimally invasive implantation techniques that preserve soft tissues and have implants with bigger diameters of the head [54], as their dislocation requires a bigger force to destabilize the implant [55,56]. Therefore, bipolar prostheses and prostheses with large heads are less prone to dislocation [57]. Hence, they are commonly implanted in patients with neuromuscular disorders [58,59]. Their additional advantage is an increased surface of the contact area between working parts, decreasing the net loading over the surface (pressure), thus minimizing the risk of their abrasion, fragmentation, and creep. Abrasion and fragmentation of a polyethylene insert compromise the congruity of an implant, decreasing its resistance to dislocation. Under such circumstances, the implant should be replaced as soon as possible. Unfortunately, in THA, a higher diameter of the head decreases the range of motion in joints. Its impingement with the acetabular edge in extreme joint positions can lever the head, leading to dislocation.

Heads of higher diameter (eg, 32 mm) conflict with the acetabulum easier than smaller ones (28 mm). Moreover, their application imposes the use of polyethylene inserts of a smaller thickness, jeopardizing its durability [60-62]. Therefore, according to Kelley et al [63], each size of the head should be assigned to an accurate diameter of the acetabulum. Thus, heads of 22 mm diameter could be used with an acetabulum with a diameter up to 50 mm; heads of 26 mm in diameter are suitable with acetabular head diameters of 52 of 54 mm; heads of 28 mm in diameter are suitable with acetabular head diameters of 56 to 60 mm; and a head diameter of 32 mm requires an acetabulum with a diameter greater than 62 mm. Also noteworthy, the relationship between the diameter of the prosthesis head and the width of the neck of its stem should be preserved, as a combination of a small head with a wide neck of the stem increases the risk of implant dislocation [64].

The most common complication of THA is dislocation manifested by instability of the prosthesis, which requires further revision procedures. To avoid the risk of instability, the concept of dual mobility of hip prostheses has been developed. Multiple studies have shown that dual mobility has a statistically significant lower incidence of dislocations, when compared to standard THA. Its use is particularly promising in patients at high risk of femoral neck fractures. Dual mobility is less expensive and more usable than standard THA bearings [6,65].

Conclusions

In conclusion, the idea of implant choice individualization involving the selection of implants that would be most suitable for a patient undergoing THA and his or her activity level and expectations is becoming increasingly popular. A careful biomechanical analysis has shown that widely accepted rules of the recommended implant selection and implantation do not exclude the conflict between its elements or between the femur and the pelvis. The "safety area" introduced by Lewinnek (inclination 40±10° and anteversion 15±10°) of acetabulum positioning does not exclude the risk of ischiofemoral conflict, despite the fact that its placement outside this zone is responsible for up to 70% of dislocations [66]. A careful and delicate preparation of tissues, preserving muscles and their attachments, avoiding the release of muscle attachments and osteotomies, and their careful reattachments and stabilization avoid later dysfunctions leading to dislocation. Muscular insufficiency, when present, as well as joint congruency could be improved by the correction of an implant offset. Proper postoperative care focused on elaboration and strengthening of the desired locomotor habits, patient education on implant displacement and adequate preventive measures, risk minimization, and the negative impact of concomitant diseases that increase the risk of additional injuries can prevent this complication.

Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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"Predisposition of hip prosthesis component positioning on dislocation risk: Biomechanical considerations based on finite element method analysis."

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Article

Predisposition of Hip Prosthesis Component Positioning on Dislocation Risk: Biomechanical Considerations Based on Finite Element Method Analysis

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Abstract

Background/Objectives: Total hip arthroplasty (THA) is a widely accepted and effective intervention for advanced degenerative hip disease. However, prosthetic dislocation remains one of the most common postoperative complications. This study aimed to evaluate the biomechanical consequences of implant positioning variations and their influence on prosthetic stability. **Methods:** A three-dimensional finite element model (FEM) of the pelvis and hip joint was developed using SolidWorks Professional 2025, based on CT imaging of an anatomically normal adult. Multiple implant configurations were simulated, varying acetabular cup inclination and anteversion angles, femoral stem depth, and femoral offset. Muscle force vectors replicating single-leg stance conditions were applied according to biomechanical reference data. The mechanical performance of each configuration was quantified using the safety factor (SF), defined as the ratio of allowable material stress to calculated stress in the model. **Results:** The configuration with 45° cup inclination, 15° anteversion, standard femoral offset, and optimal stem depth demonstrated the highest SF values (9–12), indicating a low risk of mechanical failure or dislocation. In contrast, malpositioned implants—particularly those with low or high anteversion, excessive offset, or shallow stem insertion—resulted in a marked decrease in SF values (2–5), especially in the anterosuperior and posterosuperior quadrants of the acetabular interface. **Conclusions:** The findings underscore the critical importance of precise implant alignment in THA. Even moderate deviations from optimal positioning can substantially compromise biomechanical stability and increase the risk of dislocation. These results support the need for individualized preoperative planning and the use of assistive technologies during surgery to enhance implant placement accuracy and improve clinical outcomes.

Keywords: total hip arthroplasty; dislocation; finite element method; numerical analysis

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1. Introduction

Total hip arthroplasty (THA) is the most widely used surgical procedure nowadays, restoring joint function by replacing anatomical components that were damaged by pathological processes in advanced osteoarthritis. It enables almost immediate release of pain relief and recovery of limb function impaired by the disease. Due to its high efficacy the procedure enjoys widespread global popularity. It is estimated that approximately one million THA procedures are performed annually [1].

Although the procedure is relatively safe, it is not without the risk of complications. Dislocation is considered one of the more commonly reported mechanical complications following total hip arthroplasty, with incidence rates ranging from 0.2% to 10% depending on surgical approach, implant selection, and patient-related factors [2]. In many cases, dislocation necessitates additional intervention, most often closed reduction, and in some cases revision surgery. Dislocations most commonly occur within the first 6–12 weeks after prosthesis implantation and are frequently the result of improper positioning of components or excessive impingement between the femoral head and acetabular cup [3].

Understanding the biomechanics of the prosthetic hip joint is crucial for establishing optimal implantation principles. Such knowledge enables analysis of the distribution of forces acting on the prosthesis during limb loading. The direction and magnitude of these forces can compromise joint stability and, under certain external conditions, predispose to dislocation. These forces result from both the mechanical load transmitted through the joint and the tension generated by the activity of specific muscle groups, primarily the quadriceps femoris, iliopsoas, gluteus minimus and medius and indirectly maximus as well, adductors, and rotators [Figure 1]. Repetitive sub-failure cycles can accumulate micro-damage and reshape local stress–strain fields, thereby elevating fatigue failure risk. Recent data-driven work demonstrates that spatial–temporal patterns extracted from these fields can predict ligament fatigue mechanisms and failure risk, complementing conventional finite-element analyses [4].

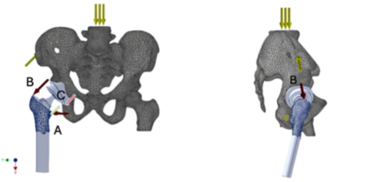

Figure 1. Muscle force vectors analyzed in the study acting on the prosthetic hip joint: adductor group (**A**), gluteal muscles (**B**), and iliopsoas muscle (**C**). Load distribution during single-leg stance is presented (↓↓↓).

The amplitude and timing of their contractions are precisely coordinated by the nervous system, producing a resultant force that enables the execution of desired movements, stable support, and effective weight transfer [5].

Dislocations of hip prostheses are among the most frequent complications of total hip arthroplasty. They result in the rupture of soft tissues stabilizing the prosthetic joint, including the joint capsule and the scar tissue forming at the site of iatrogenic injury during implantation, as well as muscular structures and their attachments. Consequently, neurovascular structures may also be secondarily affected. These complications often lead to joint instabilities and recurrent dislocations.

Decades of clinical observations and analyses have facilitated the development of what is currently considered the optimal method for prosthesis implantation. The key principle is the accurate restoration of the anatomical parameters of the native hip. These parameters include limb length, acetabular inclination angle (the angle of the acetabular cup in the coronal plane relative to the horizontal plane), acetabular anteversion, femoral

stem antetorsion, and the offset (the distance from the center of the femoral head to the femoral shaft axis). It has been observed that adherence to these principles minimizes dislocation risk, whereas deviations increase the risk of dislocation. This is attributed to the preservation (or lack thereof) of the equilibrium of mechanical forces acting on the implant. An imbalance in force vectors and amplitudes can lead to instability and, ultimately, dislocation due to loss of contact between the prosthetic components.

It should be noted that the acceptable range for each implantation parameter is relatively broad (e.g., acetabular inclination of 45° ± 10°). This variability reflects the significant role of external forces—such as trauma from stumbling, falling down, or strong impacts—in the pathogenesis of dislocation. Avoidance of such events allows for greater tolerance in component positioning while still maintaining joint stability.

The aim of this study was to demonstrate the differences in mechanical loads within the prosthetic hip joint implanted according to standard anatomical principles (acetabular inclination 45°, anteversion 15°; standard offset; and femoral stem depth placing the prosthesis rotation center at the level of the contralateral hip joint) compared to a prosthesis implanted with deviations from these principles: 60° acetabular inclination, anteversion of 0° and 30°, increased offset by 1 cm, and insufficient femoral stem depth by 2 cm. The analysis was conducted using numerical boundary problem-solving techniques and 3D interpolation within the finite element method framework.

2. Materials and Methods

A three-dimensional model of the pelvis and hip joints was obtained by processing sample pelvic computer tomography (CT) images of an individual without anatomical abnormalities. The DICOM data were imported and processed using Scilab 2024.0 (Esi Group), where filtering and segmentation procedures were applied to isolate bone tissue. This enabled the creation of a detailed 3D reconstruction of the bony pelvis.

CT data were processed in Scilab 2024.0, and the grayscale values (Hounsfield units) were converted into bone density values using phantom-based calibration (QRM-BDC, QRM GmbH, Möhrendorf, Germany), ensuring accurate mapping of local mechanical properties via Keller's equation.

Material properties were then assigned to individual bone structures using Keller's equation, which accurately reflects mechanical characteristics based on the following formula [6]:

$$E = a \cdot \rho^{b};$$

where

E—Young's modulus [MPa].

a, b—empirically determined coefficients, depending on the type of tissue, defined separately for trabecular and cortical bone. In this study, values of $a = 10.5$ and $b = 2.57$ were adopted.

ρ—density of the modeled bone tissue [g/cm^3]. The adopted value in this study was $\rho = 1.2$ g/cm^3.

$$E = 10.5 \cdot (1.2)\hat{\ }2.57 \text{ GPa} \approx 17.4 \text{ GPa}$$

This value was found to be consistent with those reported in the literature [7].

By utilizing grayscale values from computer tomography (CT) images, a distribution of material groups was achieved within the 3D model. This allowed the assignment of local material properties to individual finite elements based on their corresponding local tissue density. Consequently, it was possible to compute a local, equivalent Young's modulus for various bone regions according to their actual densities. Subsequently, an appropriate boundary conditions were then defined, constraining the translational and

rotational degrees of freedom at anatomically defined fixed points, the sacroiliac joints and the pubic symphysis, reflecting pelvic stability during single-leg stance. External loads, including body weight and muscle force vectors acting on the hip joint, were considered to replicate physiological conditions as closely as possible.

A simplified contact modeling approach was applied. As a result, a biomechanical mathematical model was constructed to simulate phenomena occurring at the interface between the implant and the surrounding bone structures.

Based on numerical modeling and simulations conducted using the finite element method (FEM), the actual geometry of the hip joint was reconstructed. The developed model, created in SolidWorks Professional 2025 (Dassault Systèmes SolidWorks Corp., Waltham, MA, USA), served as the basis for strength analysis. Prosthetic components were virtually implanted using 3D modeling tools, simulating a total hip arthroplasty procedure and resulting in a hip joint model with the endoprosthesis in situ.

For the purpose of analysis, parameters of a standard uncemented femoral stem (Medgal Hip, Medgal, Poland) were used, with a 52 mm hemispherical acetabular cup and a 32 mm spherical femoral head. The initial positioning of the acetabular cup was set at 45° inclination and 15° anteversion [Figure 2].

Figure 2. Three-dimensional model of pelvis with implanted endoprosthesis used in current work. Antero-posterior (**left**) and lateral (**right**) views.

The prosthesis components were modeled as linearly elastic and isotropic. Material properties corresponding to Ti-6Al-4V were considered for both the titanium alloy stem and cup, i.e., Young's modulus E = 110 GPa. For the CoCrMo alloy head, E = 210 GPa was assumed, and for the UHMWPE polyethylene insert, E = 1.0 GPa.

A series of implantation scenarios were developed for the prosthesis within the hip joint, varying the positioning of both the acetabular cup in the pelvis and the femoral stem within the proximal femur. These scenarios were prepared as mathematical models for finite element simulations. The computational solvers used were FFEPlus and Direct Sparse provided by the SolidWorks engineering suite.

Simplified reference conditions were applied in the model consisting of a global gravitation force and local muscle force vectors corresponding to specific muscle groups. The bone structures were modeled using a homogeneous orthotropic material, while the prosthetic components were assigned material properties based on their real-life compositions.

Muscle force models acting on bone structures (with prosthetic elements implanted) were developed as resultant force vectors representing the load on the hip joint during single-leg stance. The muscle groups and their roles included:

- Gluteal muscles—thigh abduction and primary stabilizers of the pelvis in the coronal plane;
- Iliopsoas—hip flexor;
- Adductor muscles—thigh adduction and internal rotation.

The muscle force vector values were adopted from literature sources [8], using an average force equivalent to 3–4 times body weight, expressed in Newtons (N).

The study was designed as a comparative analysis of multiple implantation scenarios (varying cup positioning, stem insertion depth, and femoral head offset) under consistent reference conditions—identical body weight loads, muscle force magnitudes, and muscle attachment locations. Each simulation aimed to visualize the mechanical load distribution—namely stress, strain, and resulting deformations—as well as the safety factor (SF) within the analyzed anatomical region (pelvis, hip joint, and proximal femur).

The objective was to assess whether these values could exceed critical thresholds, potentially leading to prosthetic component dislocation. The analysis specifically focused on the orientation of the acetabular component (inclination, anteversion) and the femoral stem (depth of insertion, offset) in the proximal femur.

The primary parameter evaluated was the Safety Factor (SF), which quantifies the structural strength margin as the ratio between the maximum allowable load and the anticipated operational load on the prosthetic components. The selection of SF as a core evaluation metric reflects its universality and its ability to clearly delineate the boundary between the safe usage and the risk of structural failure. It is also a direct indicator of biomechanical durability and potential implant dislocation risk.

The Safety Factor was not used as a direct predictor of dislocation, but rather as a biomechanical indicator of localized overload or instability at the implant-bone and implant-liner interfaces. While dislocation is a multifactorial clinical event involving soft tissue, neuromuscular control, and component alignment, it is biomechanically linked to localized stress concentrations that can result in loss of contact between articulating surfaces (e.g., femoral head and polyethylene liner). In our FEM simulations, regions with low SF values (<3) consistently correlated with mechanical configurations known from clinical literature to be associated with a higher dislocation risk (e.g., excessive anteversion, shallow stem insertion, increased offset).

In the presented model, SF allowed a clear interpretation of how changes in prosthetic component orientation (cup and stem) affect mechanical loading. It also identifies implantation variants that fail to provide adequate safety margins [Figure 3]. Clinically, SF is a key factor while choosing optimal implant placement strategies and may also direct the proper decisions regarding surgical technique or implant design modifications. SF values in the range of 2.0–3.0 are considered associated with a high risk of mechanical failure, whereas values exceeding 6.0 are deemed safe and favorable for long-term implant integrity [9].

Particular attention was paid to the contact zone between the femoral head and the polyethylene liner of the prosthesis—i.e., the critical area where dislocation typically occurs.

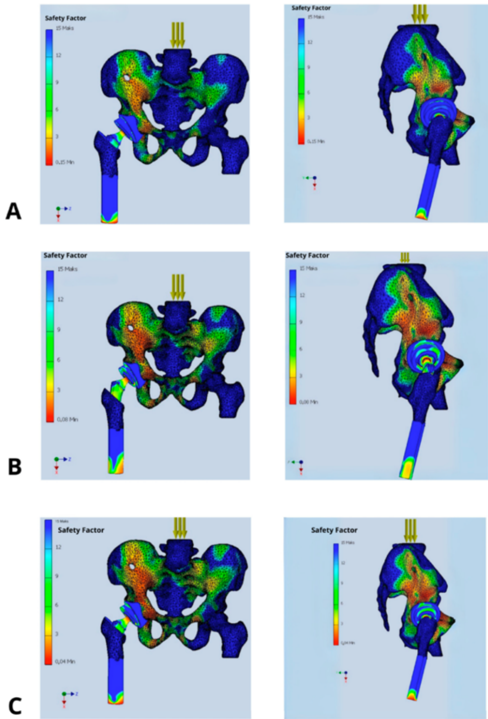

Figure 3. *Cont.*

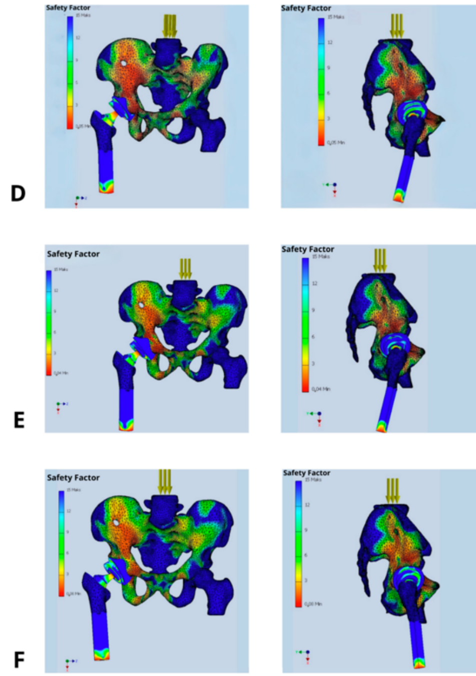

Figure 3. Distribution of Safety Factor within the hip prosthesis in different implant's configurations: (**A**) implantation recommended by the manufacturer (acetabular inclination 45°, anteversion 15°, standard offset, and femoral stem depth positioning the prosthetic axis at the level of the contralateral hip joint), (**B**) femoral stem inserted 2 cm too shallowly, (**C**) acetabular inclination increased above 50°, (**D**) acetabular anteversion increased to 30°, (**E**) acetabular anteversion reduced to 0°, and (**F**) femoral head offset increased by 1 cm.

3. Results

In the model with proper position of implant components the Safety Factor (SF) ranged from 9 to 12. Deviations from this optimal configuration resulted in a decrease in SF values:

1. In the model with femoral stem implanted 2 cm too shallowly, SF values dropped to 2–3 in the anterosuperior and anteroinferior quadrants of the acetabulum.
2. With acetabular inclination increased beyond 50°, SF values decreased to 3–4 in the anterosuperior and posterosuperior quadrants.
3. With acetabular anteversion increased to 30°, SF values dropped to 2–3 in the anterosuperior and posterosuperior quadrants.
4. With acetabular anteversion reduced to 0°, SF values fell below 5, and locally to 2–3 in the posterosuperior quadrant.
5. With an increased femoral head offset of 1 cm, SF values decreased to 3–4 in the anterosuperior and anteroinferior quadrants of the acetabulum.

4. Discussion

In most of the cases dislocation of the prosthesis is attributed to technical errors during implant placement, particularly inaccuracies in the orientation of the acetabular component. Consequently, preventive measures against this complication focus both on ensuring proper implant positioning and selecting the most appropriate implant type for a given clinical scenario [10]. Increasingly, constrained liners and dual mobility cups are being utilized, as they enhance joint congruency and thereby reduce the risk of dislocation [11]. Dual mobility acetabular components combine a small prosthetic head that articulates within a mobile polyethylene liner, which itself is free to move within the metal acetabular shell. This design not only minimizes the risk of dislocation but also increases the range of motion of the prosthetic joint, which is particularly advantageous in elderly patients and those at high risk of joint instability [12].

The efficacy and utility of such solutions are most frequently assessed retrospectively by analyzing dislocation rates. Mathematical modeling offers an alternative approach, enabling prediction of implant behavior through analysis of the forces acting upon its components [13,14]. The use of dedicated engineering software allows for the creation of a mathematical model of the hip joint, in which various prosthesis configurations can be analyzed to assess their associated benefits and risks [15,16].

In the present study a biomechanical mathematical model was developed based on the finite element method. It incorporated anatomical features of the hip joint as well as muscle activity. The objective of the model was to assess the Safety Factor and to analyze how different prosthesis configuration, including offset, anteversion, inclination, and femoral stem depth, influence joint's stability. Obtained results confirm that proper alignment of the prosthetic components, both the femoral stem and the acetabular cup, significantly reduce the risk of dislocation after total hip arthroplasty.

The analysis demonstrated a substantial impact of implant's positioning on its stability, expressed by value of the Safety Factor. Only the configuration deemed optimal, in which the acetabular cup is placed at 45° inclination and 15° anteversion, with the prosthetic axis of rotation aligned with the contralateral hip joint, offset ensuring symmetry in mechanical axis displacement relative to the body's midline, and stem positioning ensuring equal leg length resulted in biomechanical equilibrium of the acting forces. This was reflected in high SF values ranging between 9 and 12 indicating low risk of dislocation, loosening, or component failure. Other configurations with deviations in inclination, anteversion, stem depth, or offset caused a significant reduction in SF values to the range of 2–5, being most strongly expressed in the antero-superior and postero-superior quadrants of the acetabulum.

Literature examples emphasizes that precise acetabular positioning within the so-called functional safe zone is essential for minimizing biomechanical complications. According to Teja et al. [17] even minor deviations outside the 30–50° inclination and 5–25° anteversion range can impair prosthesis biomechanics and compromise functional stability. Observed in our studies decrease in SF to values as low as 2–3 in models with increased anteversion (30°) and shallow stem insertion highlights the sensitivity of these parameters and aligns with clinical findings, finding its confirmation in our clinical observations [Figure 4].

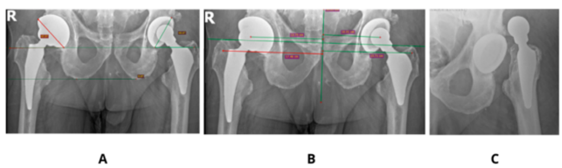

Figure 4. Clinical case showing an acetabulum with increased anteversion and inclination angle 60°—(**A**,**B**). Dislocation of the same prosthesis—(**C**).

Optimizing implant positioning is crucial for ensuring mechanical stability, and in this study, a configuration involving 45° of acetabular inclination, 15° of anteversion, standard femoral offset, and appropriate stem insertion depth was associated with favorable Safety Factor (SF) values. Nevertheless, such outcomes must be interpreted within the context of individual biomechanical variability.

Patient-specific factors, including pelvic tilt and femoral morphology (e.g., neck-shaft angle, femoral version, and offset), substantially influence prosthetic component orientation and joint stability. Prior research by Yang et al. [18] demonstrated that minor alterations in pelvic tilt (5–10°) can significantly impact functional anteversion, increasing the risk of prosthetic impingement or dislocation [Figure 5].

Figure 5. An example of an implant inserted with 0° anteversion of the acetabulum—(**A**), and its dislocation—(**B**).

Moreover, postoperative changes in pelvic alignment—resulting from neuromuscular adaptation or compensatory postural adjustments—can secondarily increase acetabular inclination and anteversion, thereby lowering local SF values. This is consistent with our findings, in which increased anteversion was associated with SF values as low as 2–3.

These findings reinforce the need for individualized surgical planning that incorporates not only anatomical variation but also dynamic postural factors, to enhance implant longevity and reduce the incidence of mechanical complications.

A review of literature on the biomechanical impact of increased femoral offset after arthroplasty reveals a notable correlation between experimental and clinical outcomes. While increasing femoral head offset improves joint stability, it may also elevate rotational loads, reducing SF at the prosthesis-liner interface, particularly in the anterosuperior and anteroinferior quadrants of the acetabulum.

Shimizu et al. [19] found that increasing femoral neck offset improves joint stability, but excessive offset leads to higher abductor muscle moments, thereby increasing load on the prosthetic joint. Similarly, Bahl et al. [20] showed that a longer abductor lever arm generates greater torque, resulting in higher contact forces and potentially reduced SF at the head–liner interface.

Avhad et al. [21] demonstrated that although high offset can improve joint function and reduce the risk of dislocation, an excessive offset increases the moment of flexion forces and imposes disproportionate loading on the acetabular component. These changes may degrade the component's congruency and increase the risk of loosening, which is expressed by SF values dropping below 4 an, pointing out the increased risk of dislocation.

The use of assistive technologies, such as computer navigation and robotics, significantly increases the precision of positioning endoprosthesis components. Zhang et al. [22] reported that navigation systems reduce the incidence of cup mispositioning by up to 50%, which translates into higher and more uniformly distributed postoperative SF values. This highlights the clinical necessity of using advanced technologies to maintain optimal implant's safety margins.

The lowest observed SF values (2–3), which are associated with a high risk of implant dislocation, are consistent with findings by Maratt and D'Lima [23], and Widmer [24]. Their studies confirm that both increased and decreased anteversion adversely affect hip prosthesis stability and substantially increase the risk of dislocation.

A limitation of this study was the exclusive analysis of single-leg stance with body weight loading during upright posture. We have also decided not to analyze observed in our studies lowering of SF in other than acetabular insert—prosthetic head parts of the implant, focusing on the mechanism of implant's dislocation. Nevertheless, as could be observed in Figure 3 their lowering up to 2–3 threatening implant's loosing (at the border between acetabular cup and pelvic bone, as well as around the medical aspect of the femoral stem) or periprosthetic bone fracture (at the apex of the stem).

The SF in this study was assessed under static loading conditions simulating single-leg stance. Despite the simplified loading scenario, low SF values (e.g., <3) may indicate areas of mechanical vulnerability with limited capacity to accommodate increased stress. In clinical practice, dislocations frequently occur during dynamic activities or accidental trauma, where joint loads can rise sharply within milliseconds. Under such circumstances, implant configurations operating close to their structural limits are at markedly increased risk of micromotion, interface failure, or dislocation. Consequently, SF can be interpreted as a surrogate marker of biomechanical resilience, reflecting the implant's ability to withstand both physiological and non-physiological loading conditions.

Clinical observations suggest that dislocations in most cases take place on activities that significantly differ from this model, such as falling from the bed, slipping, descending the stairs, or due to other trauma-related events, where limb's positioning and muscle's tensions are difficult to predict [25]. Particularly vulnerable are patients with impaired cognition (e.g., due to dementia) or those under the influence of alcohol or psychoactive

substances. In this particular group of patients, the postoperative risk of dislocation may be up to four times higher than that in the general population [26].

While an optimal implant positioning significantly reduces risk of dislocation, postoperative factors—including patient compliance, physical therapy protocols, and cognitive or functional impairments—are equally critical. Clinical observations and literature data suggest that in most cases dislocations occur due to unpredictable activities. Therefore, patient's education, an appropriate rehabilitation, and tailored movement restrictions must be an integral component of postoperative care supporting the mechanical stability of the implant. Future biomechanical studies could investigate the effects of typical at-risk patient movements during rehabilitation, such as flexion combined with internal rotation, which are known to be responsible for posterior dislocation.

In summary, our results confirm the critical importance of proper prosthesis component positioning for maintaining high Safety Factor values. Furthermore, the identification of mechanically vulnerable regions (e.g., prosthetic head–liner interface, anterosuperior acetabular quadrant, stem tip) is essential for optimizing treatment strategies and postoperative monitoring. This underscores the need for precise preoperative planning and the intraoperative use of support technologies in clinical practice.

One of the most important limitations of this study is the use of a single anatomical model derived from a CT scan of an individual with normal hip morphology. While this enabled a standardized analysis of implant positioning, it does not capture the anatomical variability seen in clinical populations. In particular, patients with osteoporosis or hip dysplasia may exhibit markedly different bone quality and joint geometry, which can significantly affect load transmission, implant fixation, and the resulting biomechanical safety margins. Future studies should incorporate population-specific anatomical datasets or parametric modeling approaches to account for such variability and improve clinical applicability.

5. Conclusions

- Proper positioning of the hip endoprosthesis promotes an even distribution of the Safety Factor within the acetabular component.
- The lowest Safety Factor values (2–3), associated with an increased risk of implant dislocation, are observed in cases of insufficient femoral stem insertion (increased risk of anterior dislocation), excessive acetabular anteversion (increased risk of anterior dislocation), and reduced acetabular anteversion (increased risk of posterior dislocation).
- Deviations from standard implant positioning, both in terms of femoral stem depth and acetabular cup orientation (inclination, anteversion), lead to a decrease in the Safety Factor.
- Alterations in femoral head offset reduce the Safety Factor specifically within the anterior quadrants of the acetabulum.
- Use of assistive technologies such as robotic and navigation systems significantly improves implant positioning accuracy, which translates into higher Safety Factor values and lower dislocation risk.
- In high-risk patients, computer-assisted THA may provide biomechanical advantages by minimizing malposition-related overloads and enhancing long-term implant stability.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki. A positive decision from the Bioethics Committee (No. AKBE/224/25) was issued on 3 September 2025.

Informed Consent Statement: Patient consent was waived due to the use of fully anonymized CT data from a non-identifiable individual. The dataset did not contain any personal information or metadata that could allow identification of the subject.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

THA	Total hip arthroplasty
SF	Safety Factor
FEM	Finite element method
N	Newtons
CT	Computer tomography

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Rozdział 7.

Podsumowanie

Zwichnięcie endoprotezy stawu biodrowego pozostaje jedną z najczęstszych i najbardziej poważnych powikłań po alloplastyce całkowitej stawu biodrowego (THA). Pomimo postępu w zakresie technik chirurgicznych, doboru implantów oraz opieki pooperacyjnej, ryzyko niestabilności stawu utrzymuje się, szczególnie u pacjentów z czynnikami predysponującymi.

W przeprowadzonych analizach, obejmujących zarówno przegląd literatury, jak i autorską biomechaniczną symulację komputerową z wykorzystaniem metody elementów skończonych (FEM), wykazano ścisły związek pomiędzy ustawieniem komponentów protezy a ryzykiem jej zwichnięcia. Modele matematyczne pozwoliły na precyzyjne określenie stref przeciążeń w obrębie powierzchni stawowej panewki oraz komponentu udowego w zależności od zmiennych ustawień kąta inklinacji, antewersji, głębokości osadzenia trzpienia oraz offsetu głowy protezy.

Najkorzystniejszy rozkład biomechaniczny (wyrażony wysokimi wartościami SF 9–12) osiągnięto w konfiguracji: inklinacja panewki 45°, antewersja 15°, standardowy offset oraz optymalna głębokość osadzenia trzpienia, odpowiadająca fizjologicznej rotacyjnej osi biodra. Natomiast jakiekolwiek odchylenia od tych parametrów prowadziły do znacznego obniżenia SF (5–2), szczególnie w kwadrantach przednio-górnym i tylno-górnym panewki, co jednoznacznie wskazuje na zwiększoną podatność na zwichnięcie.

Dodatkowo, w analizie przeglądowej podkreślono rolę czynników klinicznych zwiększających ryzyko destabilizacji, takich jak dostęp operacyjny (zwłaszcza tylny), niedostateczna rekonstrukcja po operacji tkanek miękkich, patologie kręgosłupa lędźwiowo-krzyżowego, choroby neurologiczne oraz zachowania ryzykowne pacjentów po operacji. Istotnym elementem strategii profilaktycznej jest także dobór odpowiedniego typu protezy – w tym implanty z głową o większej średnicy oraz konstrukcje dual mobility, których zastosowanie obniża ryzyko zwichnięcia w grupach pacjentów wysokiego ryzyka.

Wnioski

1. Precyzyjne, anatomiczne ustawienie komponentów endoprotezy (kąt inklinacji 45°, antewersja 15°, optymalna głębokość osadzenia i standardowy offset) znacząco poprawia stabilność stawu biodrowego po THA i minimalizuje ryzyko zwichnięcia.
2. Wartości współczynnika bezpieczeństwa (SF) uzyskane metodą FEM są czułym wskaźnikiem biomechanicznej stabilności endoprotezy. Wartości poniżej 3 korelują z wysokim ryzykiem uszkodzenia implantu lub jego zwichnięcia.
3. Odchylenia od zalecanych wartości ustawienia panewki i trzpienia (zarówno zbyt małą, jak i nadmierna antewersja czy offsetem) prowadzą do lokalnych przeciążeń komponentów protezy oraz zaburzenia równowagi mięśniowej.
4. Ryzyko zwichnięcia wzrasta istotnie w obecności współistniejących dysfunkcji neurologicznych, chorób układu kostno-stawowego (zwłaszcza zesztywnień kręgosłupa), deficytów

mięśniowych oraz u pacjentów nieprzestrzegających zaleceń pooperacyjnych.

5. Wdrożenie technologii wspomagających (nawigacja komputerowa, robotyka) oraz indywidualizacja planowania przedoperacyjnego stanowią kluczowe elementy poprawy precyzji wszczepienia i ograniczenia powikłań mechanicznych.
6. Dla pacjentów z grup podwyższonego ryzyka szczególnie korzystne jest zastosowanie komponentów panewkowych typu dual mobility oraz głów o większej średnicy (≥32 mm), które zwiększają kongruencję stawu i poprawiają zakres bezpiecznego ruchu.
7. Zarówno optymalizacja ustawienia protezy, jak i edukacja chorego są nieodzowne w celu minimalizacji ryzyka zwichnięcia i poprawy długoterminowych wyników leczenia operacyjnego.
8. Prawidłowe umiejscowienie endoprotezy sprzyja równomiernemu rozkładowi współczynnika bezpieczeństwa w obrębie panewki.
9. Najniższe wartości współczynnika bezpieczeństwa 2–3, zagrażające zwichnięciem implantu pojawiają się w przypadkach zbyt płytkiego osadzenia trzpienia (zwiększonego ryzyka przedniego zwichnięcia endoprotezy) oraz zwiększonej antewersji panewki (zwiększonego ryzyka przedniego zwichnięcia endoprotezy) i zmniejszonej antewersji panewki (zwiększonego ryzyka tylnego zwichnięcia endoprotezy).
10. Odchylenia od standardowego osadzenia, zarówno w zakresie głębokości trzpienia, jak i ustawienia panewki (inklinacja, antewersja), prowadzą do obniżenia współczynnika bezpieczeństwa.

11. Obniżenie współczynnika bezpieczeństwa koncentruje się w określonych kwadrantach panewki w zależności od rodzaju odchylenia.
12. Zarówno zwiększenie, jak i zmniejszenie antewersji panewki wpływa niekorzystnie na lokalne wartości współczynnika bezpieczeństwa.
13. Zmiana offsetu głowy endoprotezy wpływa na obniżenie współczynnika bezpieczeństwa w przednich kwadrantach panewki.

Rozdział 8.

Opinia Komisji Bioetycznej lub Etycznej

Komisja Bioetyczna
przy Warszawskim Uniwersytecie Medycznym

Tel.: 022/ 57 - 20 -303
Fax: 022/ 57 - 20 -165

ul. Żwirki i Wigury nr 61
02-091 Warszawa

e-mail: komisja.bioetyczna@wum.edu.pl
www.komisja-bioetyczna.wum.edu.pl

Warszawa, dnia 03.09.2025

AKBE/ 224 / 2025

Lek. Maciej Kostewicz
Klinika Ortopedii i Traumatologii Narządu Ruchu
WUM

OŚWIADCZENIE

Niniejszym oświadczam, że Komisja Bioetyczna przy Warszawskim Uniwersytecie Medycznym w dniu 03 września 2025 r. przyjęła do wiadomości informację na temat badania pt. "Predyspozycje sposobu posadowienia elementów protezy stawu biodrowego na ryzyko jej zwichnięcia. Rozważania biomechaniczne w oparciu o analizę metodą elementów skończonych". Przedstawione badanie nie stanowi eksperymentu medycznego w rozumieniu art. 21ust.1 ustawy z dnia 5 grudnia 1996 r. o zawodach lekarza i lekarza dentysty (Dz.U. z 2018r poz.617) i nie wymaga uzyskania opinii Komisji Bioetycznej przy Warszawskim Uniwersytecie Medycznym, o której mowa w art. 29 ust.1 ww. ustawy.

Przewodnicząca Komisji Bioetycznej

Prof. dr hab. n. med. Magdalena Kuźma –Kozakiewicz

Rozdział 9.

Oświadczenia wszystkich współautorów publikacji określające indywidualny wkład (udział merytoryczny i procentowy) każdego z nich w ich powstanie.

WARSZAWA 12.09.2025 (miejscowość, data)

MARCIN ZACZYK
(imię i nazwisko)

OŚWIADCZENIE

Jako współautor pracy pt. .....*Predisposition of hip prosthesis component positioning on dislocation risk: Biomechanical considerations based on finite element method analysis.* .... oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi: ...opracowanie matematycznego modelu trójwymiarowego endoprotezy stawu biodrowego z wykorzystaniem metody elementów skończonych, przeprowadzenie analizy wartości współczynnika bezpieczeństwa dla różnych konfiguracji ustawienia komponentów endoprotezy............

Wkład ...Macieja Kostewicza.........w powstawanie publikacji obejmował:
(imię i nazwisko kandydata do stopnia)

opracowanie koncepcji badawczej, analizę literatury przedmiotu, współudział w przygotowaniu metodologii, gromadzenie oraz opracowanie materiału badawczego, a także interpretację wyników i współtworzenie części dyskusyjnej wraz z końcowymi wnioskami.. ....
(merytoryczny opis wkładu kandydata do stopnia w powstanie publikacji)*

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek/mgr...Macieja Kostewicza......
(imię i nazwisko kandydata do stopnia)

.... Marcin Zaczyk (podpis oświadczającego)

*w szczególności udziału w przygotowaniu koncepcji, metodyki, wykonaniu badań, interpretacji wyników

Warszawa 5.09.24 (miejscowość, data)

Wiesław Tomaszewski
(imię i nazwisko)

OŚWIADCZENIE

Jako współautor pracy pt. ......„Narrative Review of the Mechanism of Hip Prosthesis Dislocation and Methods to Reduce the Risk of Dislocation"..... oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi:
...przygotowanie manuskryptu, obejmujące przegląd i syntezę literatury, redakcję treści oraz finalne opracowanie tekstu publikacji....
Wkład ……Macieja Kostewicza……w powstawanie publikacji obejmował:
(imię i nazwisko kandydata do stopnia)
opracowanie koncepcji badawczej, analizę literatury przedmiotu, współudział w przygotowaniu metodologii, gromadzenie oraz opracowanie materiału badawczego, a także interpretację wyników i współtworzenie części dyskusyjnej wraz z końcowymi wnioskami.. ....

(merytoryczny opis wkładu kandydata do stopnia w powstanie publikacji)*

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek/mgr…Macieja Kostewicza……
(imię i nazwisko kandydata do stopnia)

dr hab. dr n. med. Wiesław Tomaszewski, prof. nadzw.
SPECJALISTA CHIRURGII ORTOPEDYCZNEJ
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…………………………………
(podpis oświadczającego)

*w szczególności udziału w przygotowaniu koncepcji, metodyki, wykonaniu badań, interpretacji wyników

Warszawa, 12.09.2025 (miejscowość, data)

Paweł Matdyk
(imię i nazwisko)

OŚWIADCZENIE

Jako współautor pracy pt. ......„Narrative Review of the Mechanism of Hip Prosthesis Dislocation and Methods to Reduce the Risk of Dislocation"..... oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi:
...przygotowanie manuskryptu, obejmujące przegląd i syntezę literatury, redakcję treści oraz finalne opracowanie tekstu publikacji....
Wkład ……Macieja Kostewicza……w powstawanie publikacji obejmował:
(imię i nazwisko kandydata do stopnia)
opracowanie koncepcji badawczej, analizę literatury przedmiotu, współudział w przygotowaniu metodologii, gromadzenie oraz opracowanie materiału badawczego, a także interpretację wyników i współtworzenie części dyskusyjnej wraz z końcowymi wnioskami.. ....

(merytoryczny opis wkładu kandydata do stopnia w powstanie publikacji)*

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek/mgr…Macieja Kostewicza……
(imię i nazwisko kandydata do stopnia)

.... (podpis oświadczającego)

*w szczególności udziału w przygotowaniu koncepcji, metodyki, wykonaniu badań, interpretacji wyników

12.09.25 (miejscowość, data)

Grzegorz Szczęsny
(imię i nazwisko)

OŚWIADCZENIE

Jako współautor pracy pt. ......„Narrative Review of the Mechanism of Hip Prosthesis Dislocation and Methods to Reduce the Risk of Dislocation" oraz *„Predisposition of hip prosthesis component positioning on dislocation risk: Biomechanical considerations based on finite element method analysis"* oświadczam, iż mój własny wkład merytoryczny w przygotowanie, przeprowadzenie i opracowanie badań oraz przedstawienie pracy w formie publikacji stanowi:

...przygotowanie manuskryptu, obejmujące przegląd i syntezę literatury, redakcję treści oraz finalne opracowanie tekstu publikacji....

Wkład ......Macieja Kostewicza......w powstawanie publikacji obejmował:

(imię i nazwisko kandydata do stopnia)

opracowanie koncepcji badawczej, analizę literatury przedmiotu, współudział w przygotowaniu metodologii, gromadzenie oraz opracowanie materiału badawczego, a także interpretację wyników i współtworzenie części dyskusyjnej wraz z końcowymi wnioskami..

....

(merytoryczny opis wkładu kandydata do stopnia w powstanie publikacji)*

Jednocześnie wyrażam zgodę na wykorzystanie w/w pracy jako część rozprawy doktorskiej lek/mgr...Macieja Kostewicza......

(imię i nazwisko kandydata do stopnia)

....

(podpis oświadczającego)

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7171199

*w szczególności udziału w przygotowaniu koncepcji, metodyki, wykonaniu badań, interpretacji wyników