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Finite Element Study on Stability in the Femoral Neck and Head Connection to Varying Geometric Parameters with the Relates Implications on the Effect of Wear

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Abstract: Total hip arthroplasty (THA) is a common surgical procedure used to treat hip osteoarthritis and other joint conditions that cause pain and functional limitation. Traditionally, THA has been performed most often in elderly patients, but in recent years, there has been an increase in hip arthroplasties in young patients. Femoral prosthesis rupture is a rare but significant complication that can also occur in young patients undergoing total hip arthroplasty (THA). Some of the factors that can contribute to femoral prosthesis ruptures include abnormal overload, defects in the design, lack of geometric fit, and type of materials used in the stem and femoral head connection. The aim of this study is to analyze the criticalities in the contact between the femoral head and the stem neck. In particular, two types of contacts will be taken into consideration: proximal and distal, and through the finite element method (FEA), the criticalities will be defined. The results show that in the proximal contact, the stress levels exceeded 500 MPa in certain areas of the prosthesis. This stress could potentially lead to structural failure, such as rupture or deformation of the prosthesis. In addition, to prevent bacterial infiltration or debris from the outside, the distal connection is recommended.

Keywords: total hip arthroplasty; modular conical junction; materials; fem analysis

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1. Introduction

Total hip arthroplasty (THA) is a standard surgery that helps many patients relieve pain, regain mobility, and improve their quality of life. Most modern THA implant designs use a modular conical junction in which the surfaces of the head hole cone and femoral stem cone fit together and, thus, friction-controlled locking is generated. This ensures both axial and rotational stability [1]. The characteristic of modularity has become quite widespread since the 80s, as it simplifies the intervention and/or subsequent revisions. The modular components give the surgeon a high degree of freedom in the operating phase regarding the choice of components, offset, biomaterials constituting the head, and acetabular insertion. Thus, it is possible to better adapt the acetabular components, neck, and stem of the prosthesis to the patient's anatomy and hip biomechanics [2]. Modular femoral prostheses offer several advantages over standard prostheses. First of all, they allow the surgeon to customize the prosthesis according to the anatomical characteristics of the patient, ensuring better adaptation and greater stability. In addition, they can be used to address specific clinical conditions, such as hip dysplasia or femoral bone abnormalities [3]. The modulation of these prostheses also allows greater flexibility in treating patients with prosthesis wear or laxity problems, as components can be easily replaced or adjusted to improve the long-term effectiveness of the prosthesis. However, it is important to emphasize that the use of modular femoral prostheses requires specialized skills and knowledge on the part of the surgeon. It is critical that the surgeon is trained in the use of such prostheses and has a thorough understanding of the patient's specific anatomy and needs to ensure proper placement and stability of the prosthesis. In conclusion, modular femoral replacements offer a personalized treatment choice for patients who need hip replacement surgery. They allow greater flexibility in adapting the prosthesis to individual needs and can help improve long-term clinical outcomes. Despite this surgical advantage, in recent years, attention has focused on mechanically helping interstitial corrosion caused by agitation and accompanying corrosion resulting from micromovement to the modular connection. It is a process of deterioration of the prosthesis material due to interaction with body fluid, saline solutions, and other elements present in the biological environment. Corrosion of the femoral stem neck can occur when there is an unwanted reaction between the metal neck of the stem and other components of the prosthesis, such as the prosthesis head or other components that meet the neck. This situation is often associated with metal-to-metal hip replacements (MOMs) but can also occur with other types of prostheses, depending on the design and materials used. Corrosion of the femoral stem neck can lead to problems such as pain, joint instability, inflammation of surrounding tissues, damage to the surrounding bone, and other complications. Other problems include metal ion release: Corrosion can cause metal particles to be released in the surrounding area. These particles can provoke an inflammatory response in surrounding tissue and can potentially damage bone and other tissues. Formation of deposits: Corrosion can lead to the formation of deposits of oxides and other corrosive substances on the surfaces of the prosthesis [4]. These deposits can adversely affect the functioning of the joint and cause irritation or damage to surrounding tissues. Material loss: Corrosion can cause a gradual loss of material from the prosthesis, compromising its structural integrity and reducing its durability. To reduce the risk of corrosion of femoral prostheses, several strategies have been developed:

Use of corrosion-resistant materials: Materials such as titanium alloys or ceramics have been introduced that show greater corrosion resistance than traditional materials, such as metal-chrome-cobalt. Femoral stem neck corrosion is a current concern. This concern has recently been highlighted by the high failure rates of large metal-on-metal THAs attributed to adverse local tissue reactions from exposure to corrosion debris [3,4]. The National Joint Registry (NJR) documented 138,0472 hip replacements, of which 90% were first replacements and 10% were revisions. In addition, 12.5% of implant revisions were performed due to implant joint failure due to wear [3]. In addition, metal ion-related complications, such as inflammatory reactions and pseudotumors, have been linked to the head–neck junction of hip replacements [5,6]. Several aspects influence head-to-stem corrosion, including the angular discrepancy between the head and the stem pin [7,8], the assembly process in surgery [9,10], the geometry of the pin [11,12], the size of the acetabular head [12,13], the combination of articular materials [11,12,14], the roughness of the contact surface [15,16], and possible contamination at the interface [17,18]. The stability of the coupling is achieved by forcing the head on the morse cone of the neck at the time of implantation; therefore, some studies have found that a forcing of 6000 N was sufficient to ensure some stability [18].

Theoretically, the contact between the conical hollow of the head and the morse cone of the neck should be extended along the entire length of the coupling. On the other hand, due to machine tolerances, contact does not take place along the entire length of the coupling but usually in a single limited area (Figure 1). Once the semi-angle of the φ_1 morse cone of the neck and the semi-angle of the conical φ_2 slot of the head is defined, we can calculate $\varphi_3 = \varphi_2 - \varphi_1$. If $\varphi_2 > \varphi_1$, there will be limited contact at the apex of the morse cone with a reduction of the surrounding tensions inside the ceramic that constitutes the head [19]. If $\varphi_2 < \varphi_1$, there will be contact in the lower area of the morse cone. In a load condition, such that the vector changes direction with respect to the conicity, both the proximal and distal contact conditions could cause separation at the conical junction and later entry of corrosive fluids into the cone. The ingress of liquids, in conjunction with the hypoxic conditions prevailing at the junction, would aggravate corrosion. Therefore, a conical junction that does not allow the ingress of fluids can be considered a desirable design feature (Figure 2).

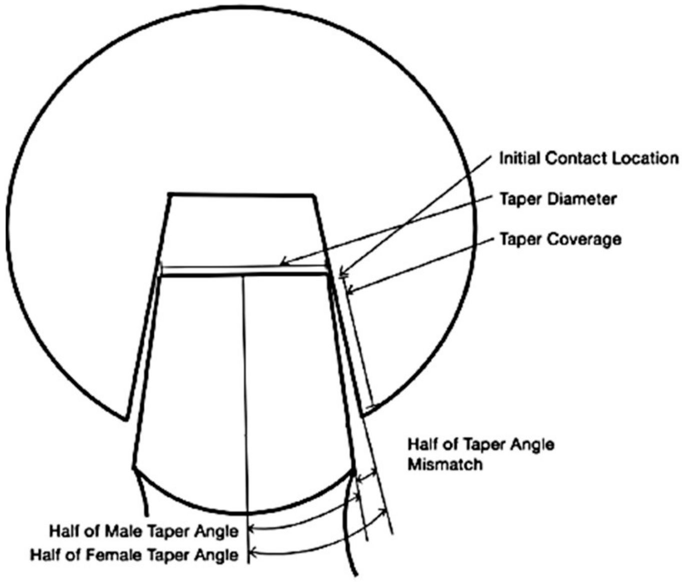

Figure 1. Coupling between morse cone and head.

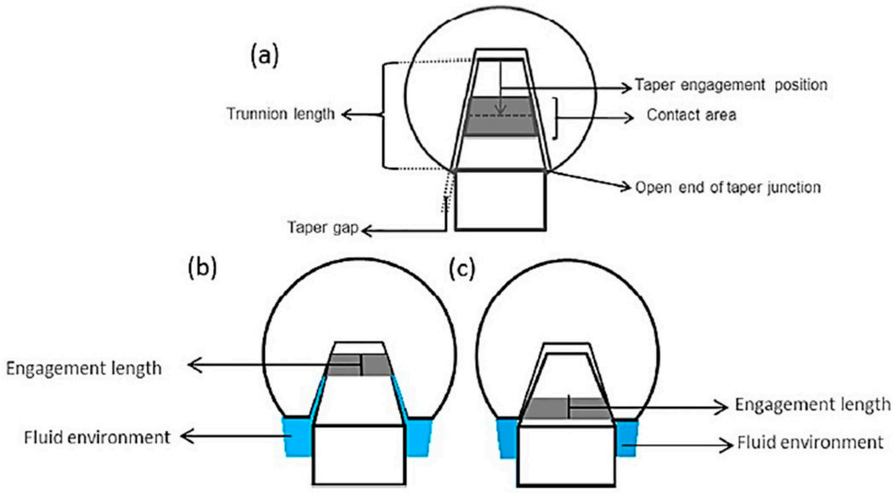

Figure 2. Geometric parameters of conical contact (**a**), proximal contact (**b**), and distal contact (**c**).

Conic geometry itself has evolved, including a reduction in both taper diameter and pin length. Reducing the taper length from 20 mm to less than 10 mm resulted in an increase in the range of motion without impact (ROM), although it also reduced the surface area available for conical contact (Figure 3). This change reduces the stability of the taper but increases the relative movement of the coupling cone under load.

The aim of this study is to evaluate, with finite element analysis (FEM), the influence of the conical contact situation in terms of differences in taper angle and contact area on the stability of the conical connection of a titanium alloy stem and ceramic head for two different conditions (Figure 4). What we want to understand is whether, as shown in other studies, a distal connection is more stable.

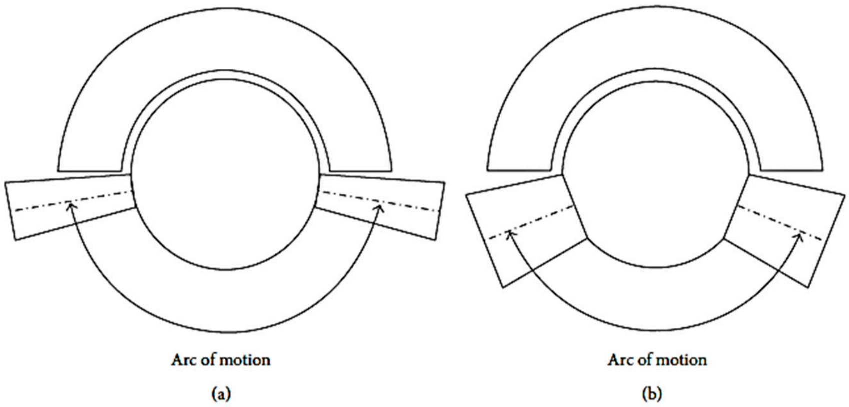

Figure 3. Increased range of motion for a smaller cone (**a**) compared to a wider cone (**b**).

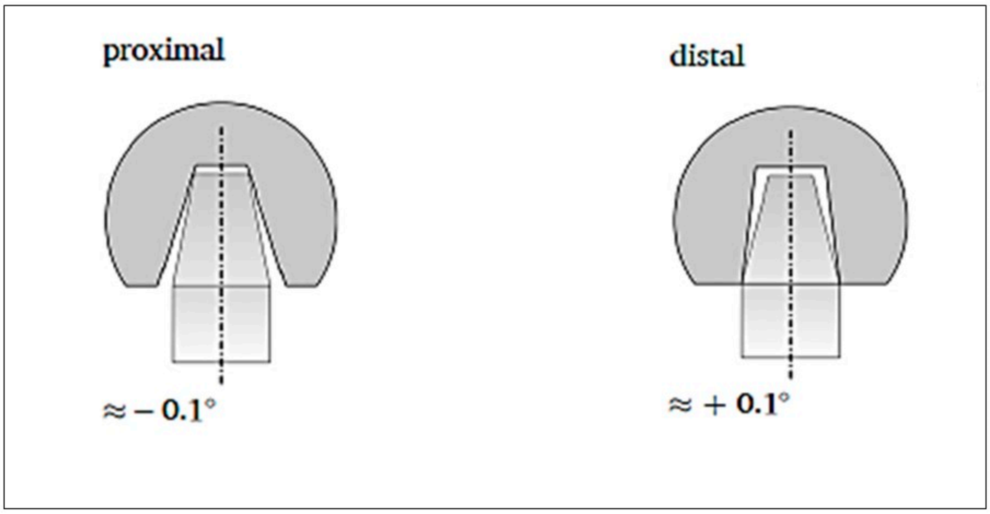

Figure 4. Model with proximal contact (**left**), model with distal contact (**right**).

2. Materials and Methods

The model of the head-to-stem pin, a conventional hip prosthesis, and its components used in this study are shown in Figure 5. Subsequently, the finite element model with standard boundary and load conditions is illustrated.

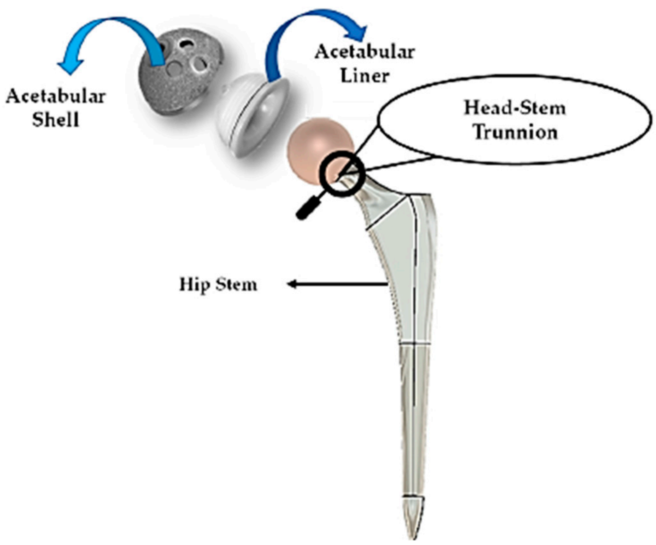

Figure 5. Components of a femoral prosthesis.

2.1. Modelling of Hip Implants

First, a hip prosthesis with smooth head–stem pins was designed. In this experiment, titanium alloy, Ti-6Al-4V [20], was selected for the stem material, and cobalt chromium alloy, Co-Cr-Mo, was selected for the acetabular head material because they are widely used in the manufacture of hip replacement systems [20–22]. Table 1 summarizes the physical characteristics of the material alloys evaluated in this study [23,24]. A 3D model of the hip implant was created using Inventor Autodesk (San Francisco, USA), a 3D modeling software platform.

Table 1. Mechanical characteristics used for this study [25].

	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Density (kg/m^3)
Ti6Al4V	110	910	1000	4400
Co-Cr	220	840	1280	8500

Autodesk 2023 and a 3D, CAD, and CAM modeling software platform were used to build the 3D model in this study. The 2D geometry and 3D CAD model view of the hip implant with 2D geometry and the 3D CAD model view are shown in Figure 6.

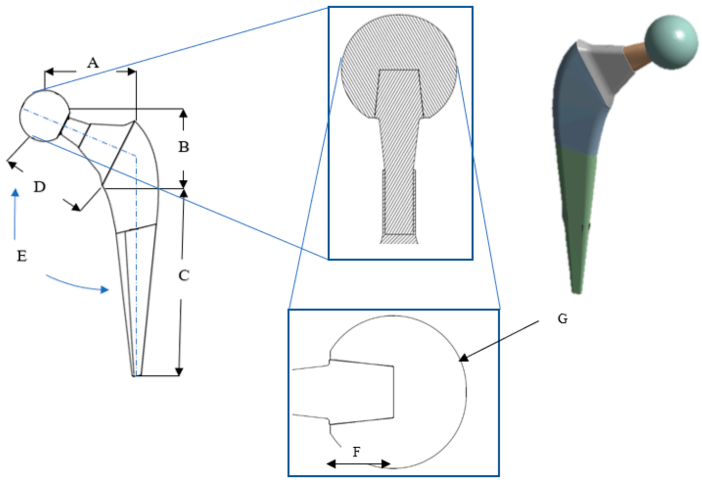

Figure 6. The size of the prosthesis analyzed in this study. Where (A = 39.5, B = 32, C = 108, D = 42, E = 135, F = 11, G = 30) mm.

In the case of contact between the head and the femoral stem, it is important to consider several aspects in FEA analysis:

Physical contact: It is necessary to define the type of contact between the head and the femoral stem, for example, a complete contact where the entire surface is in contact or a partial contact where only one party of the surface is in contact, which can be either the proximal zone or the distal area of the femoral neck. You must also specify the friction or adhesion properties between the two surfaces. For this analysis, a contact between the head and femoral stem with friction equal to 0.3 was considered [24–26]. Applied loads: It is important to define the loads and load conditions that simulate the physical activity of the patient. These can include compression loads, bending loads, or torsion loads, depending on the specific analysis you want to conduct. Constraint conditions: It is necessary to establish the constraint conditions of the model, for example, by fixing the lower end of the femoral stem to simulate fixation in the bone. Once all these aspects have been defined, FEA simulations can be performed to evaluate the stresses, deformations, and behavior of the contact between the head and the femoral stem. FEA analysis results can provide useful information about stress distribution, contact stability, and the possibility of micro-movements or potential problems, such as stress concentration.

2.2. Boundary and Loading Conditions with the Finite Element Model

In this study, boundary conditions include the fixed support zone of the plant and load conditions to estimate mechanical performance using a finite element computational model. This study follows the ISO-7206-6:2013 standard for building a mechanical fatigue test system for hip head-to-stem pin joints in computational model environments. Walking is the most common activity, while jogging is one of the most physically demanding activities. This study examines the impact of walking and jogging on subjects aged 50 to 68 years weighing between 70 and 120 kg (AVG 75 kg). The mechanical characterization of the functional load conditions of hip prostheses was presented. Figure 7 shows the resulting force of walking and jogging [27]. For 10% to 55% of each gait cycle, walking required more strength, while this was between 25% and 55% for jogging. Figure 8 shows the model where a load of 4000 N was applied at an angle of 20° on the head of the stem [28,29]. Refers to a person of 80 kg according to ISO-7206-6:2013 [30].

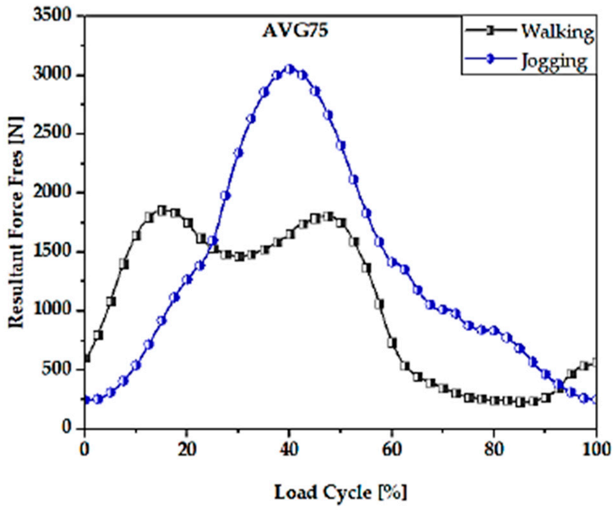

Figure 7. Resultant force values for walking and jogging loading conditions [31].

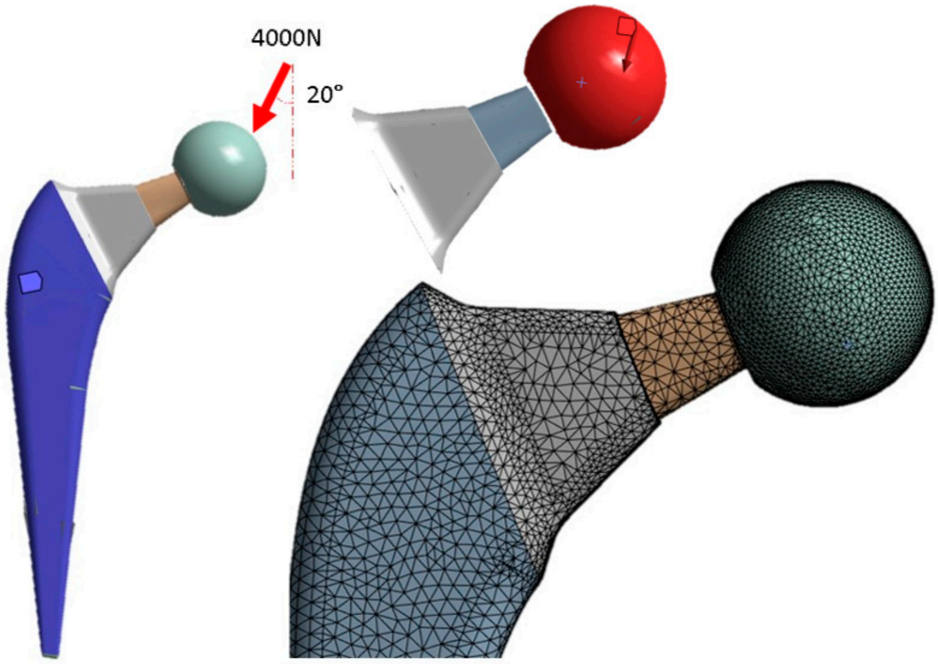

Figure 8. On the left, the application of the load on the head; on the right, the tetrahedral mesh used.

For this work, the FEM analysis was performed with an ANSYS 2023 R23 calculation program. The 3D geometry was created in Inventor and later imported into ANSYS 2023. The mesh used to discretize the 3D into small elements to facilitate resolution was 0.5 mm. Mesh thickening is a technique used in finite element analysis (FEA) to study the contact between two surfaces more accurately. When analyzing the contact between the head and the femoral stem of a prosthesis, the thickening of the mesh can help to obtain more precise results on the stresses and behavior of the surfaces in contact. In finite element analysis, the mesh is the discretization of the three-dimensional model into finite elements. A denser mesh is characterized by a greater number of smaller elements, which allows you to better approximate complex geometry and stress variations within the model. In the case of the study of contact between the head and the femoral stem, the thickening of the mesh can be conducted in areas of interest, such as the interface between the two components. By using a denser mesh in these regions, contact behavior can be more accurately captured, including local effects of pressure, stress, and deformation. Mesh thickening can be carried out by increasing the density of elements along contact surfaces or using localized refinement techniques, such as mesh refinement based on solution error criteria. This can take longer to compute as the number of items in the contact area increases. However, results obtained with a denser mesh can provide greater accuracy in the evaluation of contact and local stresses. Recent research on finite element studies based on hip replacements has used quadratic tetrahedral mesh elements [31–34] more than any other form. According to ANSYS [34], the preferred choice for complicated nonlinear geometry is tetrahedral mesh elements (Figure 8).

3. Results

The following finite element study, as can be seen in (Figures 9 and 10), shows the results obtained in the two configurations of proximal and distal contact for a femoral neck head pair in Co-Cr/Ti under a forcing load equal to 4000 N. It can be seen that in the distal contact, the stresses on the neck are limited to a small area and vary between 80 MPa and 150 MPa, while inside the hole made on the Co-Cr head, stress values of about 60 MPa are reached. However, the most stressed to bending as a result of contact in the distal area is the lower part of the head, where about 500 MPa is reached; this value could trigger cracks and risks of breakage. In the proximal contact, on the other hand, the circumferential tensions are higher and distributed over the entire surface of the neck because the contact area has decreased as a result of the same load applied, which, therefore, leads to an overall increase in tensions.

We can also observe that distal contact induces less von Mises stress on the stem neck (484 MPa) than (512 MPa) if a distal contact is considered.

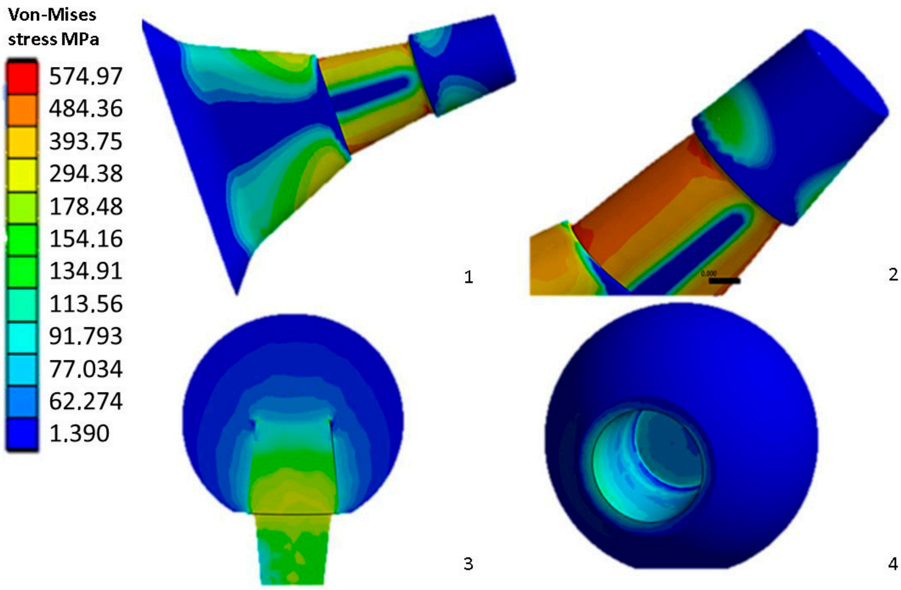

Figure 9. Results of FEM analysis of the prosthesis with head and stem contact in the distal area. ((**1**): stress von Mises on the upper stem area, (**2**): stress von Mises on the stem neck, (**3**): section showing the distribution of contact stresses between stem and head, and (**4**): von Mises stress in the conical hole of the head).

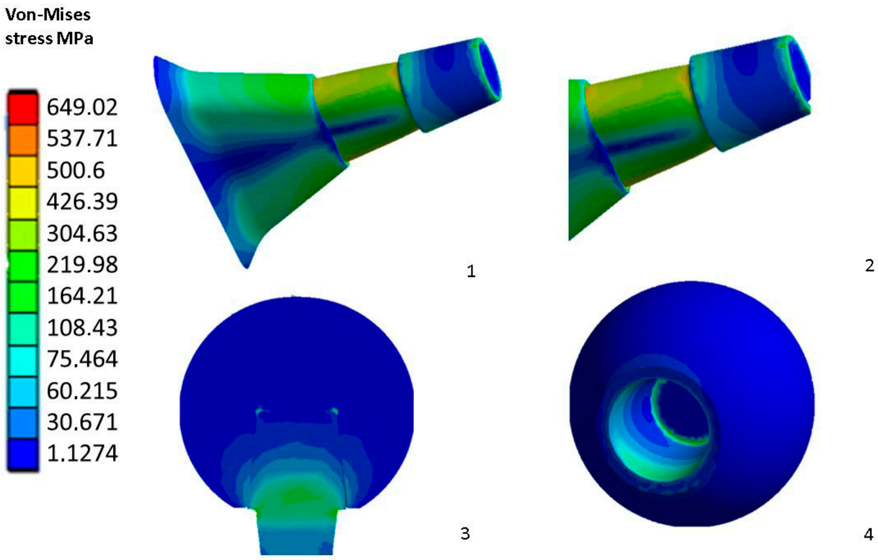

Figure 10. FEM analysis results of the prosthesis with the stem head contact in the **proximal zone.** ((**1**): stress von Mises on the upper stem area, (**2**): stress von Mises on the stem neck, (**3**): von Mises stress in the conical hole of the head, and (**4**): section showing the distribution of contact stresses between stem and head).

4. Discussion

In a laboratory study [30], the stability of the connection was measured through a torque test and an impact test. ISO 7206-13:2016. The torque test measures the torque that must be applied from the outside to compromise the stability of the cone morse connection (Figure 11).

Figure 11. Investigation procedure for determining the taper connection strength: starting with the fixation of the implant components (**left**), then the impaction of the two taper components (**middle**), and finally the torque-off test (**right**).

As can be seen from the experimental results in Figure 12, a distal contact allows a higher torque-off, therefore improving the stability.

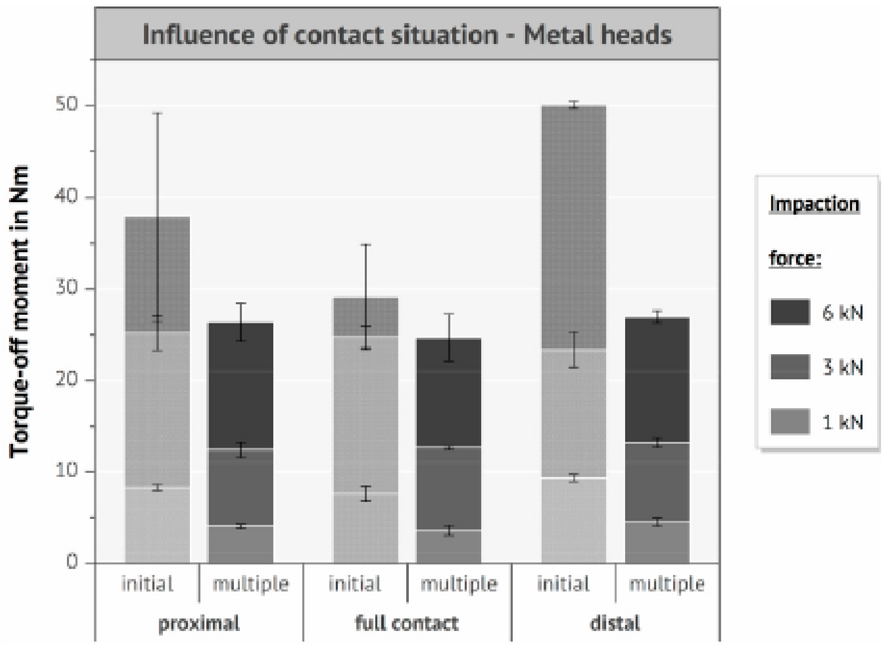

Figure 12. Influence of the contact situation on the taper strength when using metal heads.

A numerical study was performed by Fallahnezhad et al. [30,31,34] with the aim of simulating abrasive wear depending on the contact situation; increased wear for the proximal contact situation was reported. Distal contact revealed less wear. In addition, a distal contact decreases the risk, according to which physiological liquids can infiltrate the connection and compromise the re-passivation of titanium with consequences on the increase in the corrosion rate. The current study investigated the influence of geometric conic features by FEM finite element analysis considering a load of 4000 N [34]. The contact state affects stability. The complete contact situation, as can be seen from the result obtained in the laboratory, led to the lowest stability of the conical connection compared to distal and proximal contact situations. With a greater conical angular difference (proximal or distal contact situation), contact occurs over a smaller area, leading to locally increased contact pressure. A possible explanation for the increased resistance in the distal contact situation could be that the contact area is distally larger than proximal due to the conical shape of the connection. Another numerical study was conducted by Fallahnezhad et al. [34], with the aim of simulating abrasive wear depending on the contact situation (Fallahnezhad et al.) [34]. They reported increased wear due to the proximal contact situation. Distal contact revealed less wear. For this study, we used the von Mises results to analyze the connection. The von Mises stress is a parameter used to assess the state of stress within a material or structure. In this study, von Mises stress was used to compare material yield stress with neck and head stress. Finite element analysis (FEA) can be used to calculate von Mises stress in the femoral head–stem connection. The von Mises stress assessment can be combined with other critical factors, such as applied load, constraint conditions, material properties, and geometric features, to ensure proper design and accurate evaluation of the performance of the femoral head–stem connection in the prosthesis.

An increase of contact stress between the stem and the femoral head [33] of a prosthesis can be caused by several factors, including:

Geometric mismatch: If the geometry of the head and the stem is not perfectly matched, for example, due to dimensional or shape differences, a concentrated load or uneven distribution of stress at the point of contact may occur. High-applied loads: If the prosthesis is subjected to high physical loads or high-impact activities, there may be an increase of stress in the contact between the stem and the femoral head. The use of materials with different mechanical properties, such as a difference in elastic modulus or coefficient of thermal expansion, can cause an uneven discharge of stress and an increase in local stresses in the contact.

Considering the experimental results of Fallahnezhad et al. [34] and those obtained with the numerical simulation FEA, both state that distal contact is the one in which the stresses are higher and there is a greater risk of corrosion.

5. Conclusions

A comparative analysis of the tensions exchanged at the femoral prosthesis head–neck interface using the FEM method is presented. This investigation is conducted if the head is pressed to the stem with a force of 4000 N [35]. The results of this study, also compared with a study carried out in a laboratory, indicate in both tests that the distal contact is the one that guarantees greater stability even if the femoral stem is more stressed in flexion than a contact in the proximal area. The limitation of this study lies in the fact that it is not possible to study the effect of roughness on finite elements, as the results are dependent on the type of contact that is simulated numerically and the size of the mesh used. A further limitation of this study concerns the fact that the applied load is a static load. The dynamic load, on the other hand, could cause fatigue failure. Further studies and laboratory validation will be needed.

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References

1. Sharkey, P.F.; Austin, M.S.; Hozack, W. Total hip arthroplasty in the young patient. *Instr. Course Lect.* **2006**, *55*, 173–176. [PubMed]
2. Friedman, R.J.; Black, J.; Galante, J.O.; Jacobs, J.J.; Skinner, H.B. Current concepts in orthopedic biomaterials and implant fixation. *Instr. Course Lect.* **1994**, *43*, 233–255. [PubMed]

3. Osman, K.; Panagiotidou, A.P.; Khan, M.; Blunn, G.; Haddad, F.S. Corrosion at the head-neck interface of current designs of modular femoral components: Essential questions and answers relating to corrosion in modular head-neck junctions. *Bone Jt. J.* **2016**, *98*, 579–584. [CrossRef]
4. Punzi, N. Contact Analysis in "Hard-on-Hard" Hip Replacements. Master's Thesis, Department of Information Engineering, University of Pisa, Pisa, Italy, 2013.
5. Bergmann, G.; Graichen, F.; Rohlmann, A. Hip joint loading during walking and running, measured in two patients. *J. Biomech.* **1993**, *26*, 969–990. [CrossRef]
6. Bergmann, G.; Deuretzbacher, G.; Heller, M.; Graichen, F.; Rohlmann, A.; Strauss, J.; Duda, G. Hip contact forces and gait patterns from routine activities. *J. Biomech.* **2001**, *34*, 859–871. [CrossRef]
7. Bech, N.H.; Haverkamp, D. Impingement around the hip: Beyond cam and pincer. *EFORT Open Rev.* **2018**, *3*, 30–38. [CrossRef]
8. Vassalou, E.E.; Zibis, A.H.; Klontzas, M.E.; Karantanas, A.H. Imaging of impingement syndromes around the hip joint. *HIP Int.* **2017**, *27*, 317–328. [CrossRef] [PubMed]
9. Achar, S.; Yamanaka, J. Apophysitis and osteochondrosis: Common causes of pain in growing bones. *Am. Fam. Physician* **2019**, *99*, 610–618.
10. Garcia-Montoya, L.; Gul, H.; Emery, P. Recent advances in ankylosing spondylitis: Understanding the disease and management. *F1000Research* **2018**, *7*, 1512. [CrossRef]
11. Thomas, G.P.; Brown, M.A. Genetics and genomics of ankylosing spondylitis. *Immunol. Rev.* **2010**, *233*, 162–180. [CrossRef]
12. Sugano, N.; Takao, M.; Sakai, T.; Nishii, T.; Miki, H.; Nakamura, N. Comparison of mini-incision total hip arthroplasty through an anterior approach and a posterior approach using navigation. *Orthop. Clin. N. Am.* **2009**, *40*, 365–370. [CrossRef] [PubMed]
13. Treacy, R.B.; McBryde, C.W.; Pynsent, P.B. Birmingham hip resurfacing arthroplasty. A minimum follow-up of five years. *J. Bone Jt. Surg. Br.* **2005**, *87*, 167–170. [CrossRef] [PubMed]
14. Merola, M.; Affatato, S. Materials for Hip Prostheses: A Review of Wear and Loading Considerations. *Materials* **2019**, *12*, 495. [CrossRef] [PubMed]
15. Tsikandylakis, G.; Mohaddes, M.; Cnudde, P.; Eskelinen, A.; Kärrholm, J.; Rolfson, O. Head size in primary total hip arthroplasty. *EFORT Open Rev.* **2018**, *3*, 225–231. [CrossRef] [PubMed]
16. Matsushita, I.; Morita, Y.; Ito, Y.; Gejo, R.; Kimura, T. Activities of daily living after total hip arthroplasty. Is a 32-mm femoral head superior to a 26-mm head for improving daily activities? *Int. Orthop.* **2011**, *35*, 25–29. [CrossRef] [PubMed]
17. Delay, C.; Putman, S.; Dereudre, G.; Girard, J.; Lancelier-Bariatinsky, V.; Drumez, E.; Migaud, H. Is there any range-of-motion advantage to using bearings larger than 36 mm in primary hip arthroplasty: A case-control study comparing 36-mm and large-diameter heads. *Orthop. Traumatol. Surg. Res.* **2016**, *102*, 735–740. [CrossRef]
18. Pijls, B.G.; Meessen, J.M.T.A.; Tucker, K.; Stea, S.; Steenbergen, L.; Fenstad, A.M.; Mäkelä, K.; Stoica, I.C.; Goncharov, M.; Overgaard, S.; et al. MoM total hip replacements in Europe: A NORE report. *EFORT Open Rev.* **2019**, *4*, 423–429. [CrossRef] [PubMed]
19. Kocagöz, S.B.; Underwood, R.J.; Sivan, S.; Gilbert, J.L.; MacDonald, D.W.; Day, J.S.; Kurtz, S.M. Does taper angle clearance influence fretting and corrosion damage at the head{stem interface A matched cohort retrieval study. *Semin. Arthroplast.* **2013**, *242*, 246–254. [CrossRef]
20. Kao, Y.-Y.J.; Koch, C.N.; Wright, T.M.; Padgett, D.E. Flexural rigidity, taper angle, and contact length affect fretting of the femoral stem trunnion in total hip arthroplasty. *J. Arthroplast.* **2016**, *31* (Suppl. 9), 254–258. [CrossRef]
21. Goldberg, J.R.; Gilbert, J.L. Electrochemical response of CoCrMo to high-speed fracture of its metal oxide using an electrochemical scratch test method. *J. Biomed. Mater. Res.* **1997**, *37*, 421–431. [CrossRef]
22. Goldberg, J.R.; Gilbert, J.L.; Jacobs, J.J.; Bauer, T.W.; Paprosky, W.; Leurgans, S. A multicenter retrieval study of the taper interfaces of modular hip prostheses. *Clin. Orthop. Relat. Res.* **2002**, *401*, 149–161. [CrossRef] [PubMed]
23. Gilbert, J.L.; Buckley, C.A.; Jacobs, J.J. In vivo corrosion of modular hip prosthesis components in mixed and similar metal combinations. The effect of crevice, stress, motion, and alloy coupling. *J. Biomed. Mater. Res.* **1993**, *27*, 1533–1544. [CrossRef] [PubMed]
24. Lundberg, H.J.; Ha, N.Q.; Hall, D.J.; Urban, R.M.; Levine, B.R.; Pourzal, R. Contact mechanics and plastic deformation at the local surface topography level after assembly of modular head-neck junctions in modern total hip replacement devices. In *Modularity and Tapers in Total Joint Replacement Devices STP1591*; Greenwald, S.A., Kurtz, S.M., Lemons, J.E., Milhalko, W.M., Eds.; ASTM International: West Conshohocken, PA, USA, 2015.
25. Ashkanfar, A.; Langton, D.J.; Joyce, T.J. A large taper mismatch is one of the key factors behind high wear rates and failure at the taper junction of total hip replacements: A finite element wear analysis. *J. Mech. Behav. Biomed. Mater.* **2017**, *69*, 257–266. [CrossRef] [PubMed]
26. Choroszyński, M.; Choroszyński, M.R.; Skrzypek, S.J. Biomaterials for hip implants—Important considerations relating to the choice of materials. *Bio-Algorithms Med-Syst.* **2017**, *13*, 133–145. [CrossRef]
27. Maruyama, N.; Kawasaki, H.; Yamamoto, A.; Hiromoto, S.; Imai, H.; Hanawa, T. Friction-Wear Properties of Nickel-Free Co-Cr-Mo Alloy in a Simulated Body Fluid. *Mater. Trans.* **2005**, *46*, 1588–1592. [CrossRef]
28. OrthoLoad: Loading of the Orthopedic Implant. Available online: https://orthoload.com/ (accessed on 15 October 2022).

29. Fallahnezhad, K.; Farhoudi, H.; Oskouei, R.H.; Taylor, M. Influence of geometry and materials on the axial and torsional strength of the head-neck taper junction in modular hip replacements: A finite element study. *J. Mech. Behav. Biomed. Mater.* **2016**, *60*, 118–126. [CrossRef]
30. Feyzi, M.; Fallahnezhad, K.; Taylor, M.; Hashemi, R. A review on the finite element simulation of fretting wear and corrosion in the taper junction of hip replacement implants. *Comput. Biol. Med.* **2021**, *130*, 104196. [CrossRef]
31. Guzmán, M.; Durazo, E.; Ortiz, A.; Sauceda, I.; Siqueiros, M.; González, L.; Jiménez, D. Finite Element Assessment of a Hybrid Proposal for Hip Stem, from a Standardized Base and Different Activities. *Appl. Sci.* **2022**, *12*, 7963. [CrossRef]
32. ANSYS. *ANSYS Meshing User's Guide*; ANSYS: Canonsburg, PA, USA, 2013.
33. Soliman, M.M.; Chowdhury, M.E.H.; Islam, M.T.; Musharavati, F.; Mahmud, S.; Hafizh, M.; Ayari, M.A.; Khandakar, A.; Alam, M.K.; Nezhad, E.Z. Design and Performance Evaluation of a Novel Spiral Head-Stem Trunnion for Hip Implants Using Finite Element Analysis. *Materials* **2023**, *16*, 1466. [CrossRef]
34. ANSYS. *The Fundamentals of FEA Meshing for Structural Analysis*; ANSYS: Canonsburg, PA, USA, 2021; Volume 2022.
35. Wassef, A.J.; Schmalzried, T.P. Femoral taperosis: An accident waiting to happen? *Bone Joint J.* **2013**, *11* (Suppl. A), 3–6. [CrossRef]