The Impact of Varying the Femoral Head Diameter on Stability of Hip Implants

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Abstract:
Hip Implant failures have increased the number of revision surgeries in recent years due to the effect of dislocation. Hence, remedying the effect of dislocation in Hip Implants is one of the target focus for Biomechanics research scholars. The research investigates how different femoral head diameters impact on stability in complete hip replacement implants. The research used SolidWorks Premium 2025 to create seven hip implant models with Ti-6Al-4V alloy biomaterials and different femoral head diameters from 28mm to 52mm. The implants underwent finite element analysis through ANSYS 2022 R-2 to determine their deformations. The research findings show that deformations decrease when femoral head diameters increase. The 28mm femoral head diameter produced the highest deformation of 0.025918mm, but the 52mm diameter produced the lowest deformation of 0.025009mm. Studies have shown that larger femoral head diameters are associated with reduced risk of revision for dislocation and enhances stability. Hence, the research findings are acceptable and shows how different femoral head diameters affect hip implant stability.

Keywords*: Femoral Head Diameter, Hip Implant, Finite Element Analysis, Ansys, Stability, Dislocation.*

1. Introduction

The dislocation rate after total hip arthroplasty (THA) is influenced by the diagnosis and the medical condition of the patient [1], the surgical approach [2], femoral head size [1,3-4], and the skills of the surgeon through component positioning [5]. Recurrent dislocation is one of the most common reasons for reoperations in THA [3]. Small femoral head size is a risk factor for dislocation [1,3-4], . Hip implants with larger femoral heads have been developed to reduce the dislocation rate. However, larger metal-on-poly ethylene articulation increases the amount of volumetric wear debris [6]. Metal-on-metal (MoM) and ceramic-on-ceramic bearing surfaces were developed to reduce wear. MoM articulation also allowed larger head sizes in hip resurfacing arthroplasty (HRA) and THA. However, it has been shown recently that the wear propensities of many MoM designs are poor [7-8]. Large-diameter head THAs and HRAs have been used

frequently in Finland during the last decade [9-10]. Numerous studies have been performed to improve the performance of hip implants [11], including investigations into the optimal cross-section of hip implants. These assessments have involved various stem shapes, such as oval, trapezoidal, elliptical, and circular, made from different materials like Ti-6Al-4 V alloy, CoCrMo alloy, and UHMWPE. The findings indicated that trapezoidal-shaped stems experienced the least stress and deformation, with recommendations favouring the CoCrMo alloy for stem designs. Moreover, experiments have utilised Ti-6Al-4 V alloy to explore fatigue fracture development, stress, and strain concerning the hip implant. This research highlighted how stress varied, with the neck region showing the highest stress levels and thickness, while the area surrounding the crack exhibited the greatest stress [12]. In the current study, a trapezoidal cross-section stem is examined, and finite element analysis (FEA) is conducted by varying the femoral head diameter using ANSYS 2022 R-2 for a homogeneous material. This study focuses on femoral head diameters from 28 mm to 52 mm. It aims to analyse how variations in femoral head diameter affect the stability of a lightweight hip implant.

2. Materials and Methods

This investigation employs a homogeneous material. The selection of this material was based on the mechanical attributes of the human hip bone and its biological context. The mechanical characteristics of human bone are detailed in Table 1 [13].

Table 1: Mechanical Properties of Human Bone

Density (Kg/m^3)	Yield Strength (Pa)	Poisson's Ratio	Young's Modulus (Pa)
310 ± 60	1.14e 8	0.62±0.26	1.1e+10 - 2e+10

When selecting biomaterials, two primary factors must be taken into account. The first factor involves medical requirements related to the biocompatibility of the material. The second factor pertains to mechanical considerations, focusing on aspects such as wear resistance, stress concentration, and the stability of the implant [13]. Consequently, Table 2 presents the mechanical properties of biomechanical materials to aid in choosing a material that is compatible or nearly compatible with human bone [14].

Table 2: Mechanical Properties of Biomechanical Materials (MPMM)

Materials	Density (Kg/m^3)	Yield Strength (N/m^2)	Poisson's Ratio	Young Modulus (N/m^2)
Ti-6Al-4V	4430	8.8e+08	0.28	1.09e+11
UHMWPE	930	2.45e+07	0.46	6.5e+08
HDPE	964	2.95e+07	0.4	2.2e+09
Stainless Steel	8000	2.15e+08	0.27	2.1e+11

In this study, the focus is on the Ti-6Al-4V alloy due to its physical characteristics and compatibility with human bone. Ti-6Al-4V is the most widely utilised titanium alloy, accounting for approximately 50% of all titanium products available today [15]. Unlike stainless steel or

chromium-cobalt alloys, titanium and its alloys do not need a cement layer as they are biodegradable. Ti and its alloys have superior wear resistance owing to their low shear strength [16]. On the market, sterling titanium and Ti-6Al-4V are the two primary titanium-based alloys used for implantation; however, Ti-6Al-4V is increasingly replacing sterling titanium due to its enhanced mechanical strength. Therefore, Ti-6Al-4V was selected for the overall design of the hip implants (HIs). This alloy offers high strength that aligns with durability, a low density (430 kg/m^3) contributing to its lightweight nature, and a Poisson's Ratio of 0.28. Its performance is comparable to stainless steel, though marginally lower. and a Young's Modulus of 1.09e+11 N/m^2. Its corrosion-resistant properties are highly valued in biomedical applications due to significant biocompatibility. In this investigation, seven unique artificial HIs were developed using Solid Works Premium 2025. For all designs, the dimensions of the femoral stem and acetabular cup were kept consistent, while alterations were made to the size of the femoral head. The acetabular cup itself was specified with an internal diameter of 14mm and a material thickness of 7mm. alongside a trapezoidal stem with an overall length of 122.45mm and a neck shaft angle (NSA) of 140 degrees for each of the seven HIs. The femoral head is crucial in the HI design process. In this research, each of the seven femoral heads was crafted with diameters ranging from 28mm to 52mm, with a 4mm increment, to analyse the stresses generated in the femoral heads. A CAD model featuring a 28mm femoral head created with Solid Works is shown in Figure 1.

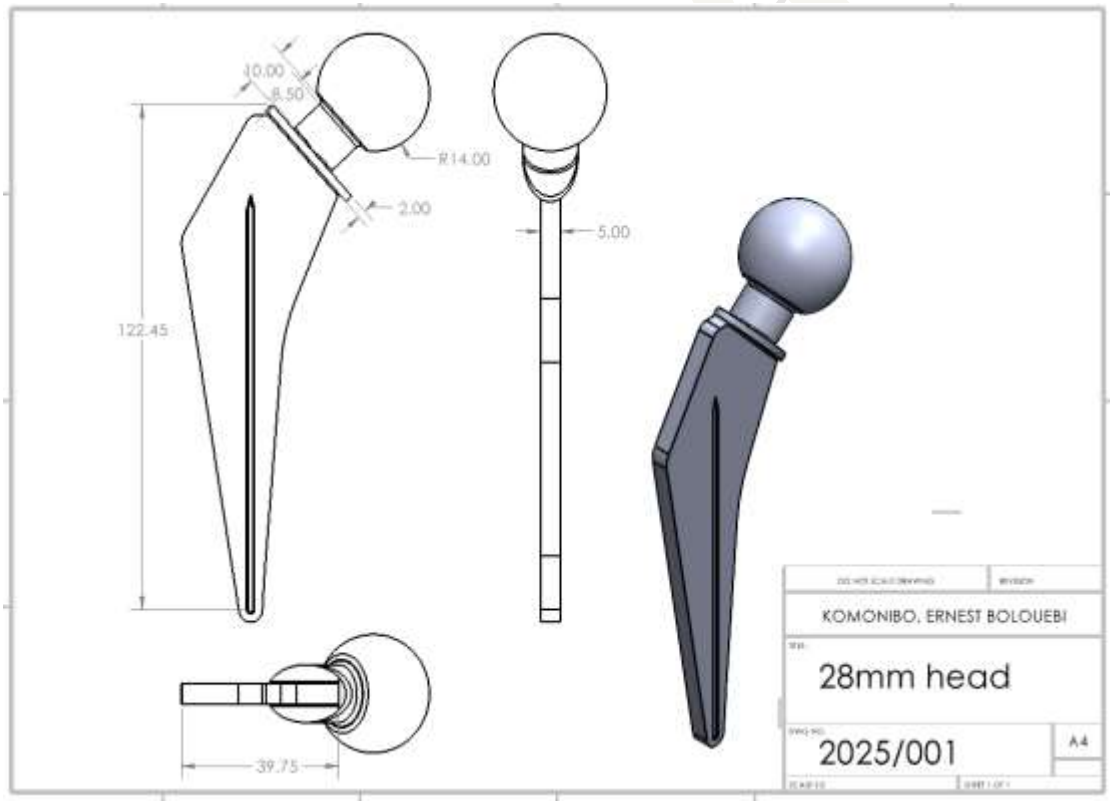


Figure 1: CAD Model for the 28mm Diameter HI

The models created were exported to ANSYS 2022 R-2 for static structural analysis, where the finite element analysis (FEA) was conducted. Additionally, SPSS software and a regression model were employed to evaluate the results derived from the FEA.

3. Mesh and Boundary Conditions

A triangular unstructured mesh was utilised to discretise the model for the numerical simulation. The femoral head and stem were discretised independently, with an element size of 0.002m for the stem and 0.0012m for the femoral head. As illustrated in Figure 2, a total of 60092 nodes and 34715 elements were created. For the mesh grid independence test, a hip implant featuring a 28 mm femoral head was examined. The constraints for the investigation followed ASTM F2996-13. Furthermore, the applied load conditions during the assessment conformed to ISO F7206-4:2010. The lower part of the stem was completely immobilised. A resultant force of 1680 N (consisting of 378 N along the X-axis and -1624 N along the Y-axis) was subsequently exerted on the surface of the backing cup, which was situated inside the femoral head, for the evaluation.



Fig 2: Mesh Report

Simulations were conducted with Ansys 2022 R-2. The deformations derived from the simulations for each of the seven distinct models are presented in Table 3, while Figure 3 illustrates the finite element analysis (FEA) for the seven different hip implants (HIs) with varying diameters of the femoral head.

4. Results and Discussion

The results, such as the deformations obtained from the simulation for each of the seven different models, are shown in Table 3, and Figure 3, shows the FEA for the seven different HI's with varying femoral head diameters.

Table 3: Femoral Head Diameters with corresponding Deformations

S/N	FEMORAL HEAD DIAMETERS (mm)	DEFORMATIONS (mm)
1	28	0.025918
2	32	0.025780
3	36	0.025698
4	40	0.025354
5	44	0.025254
6	48	0.025129
7	52	0.025009

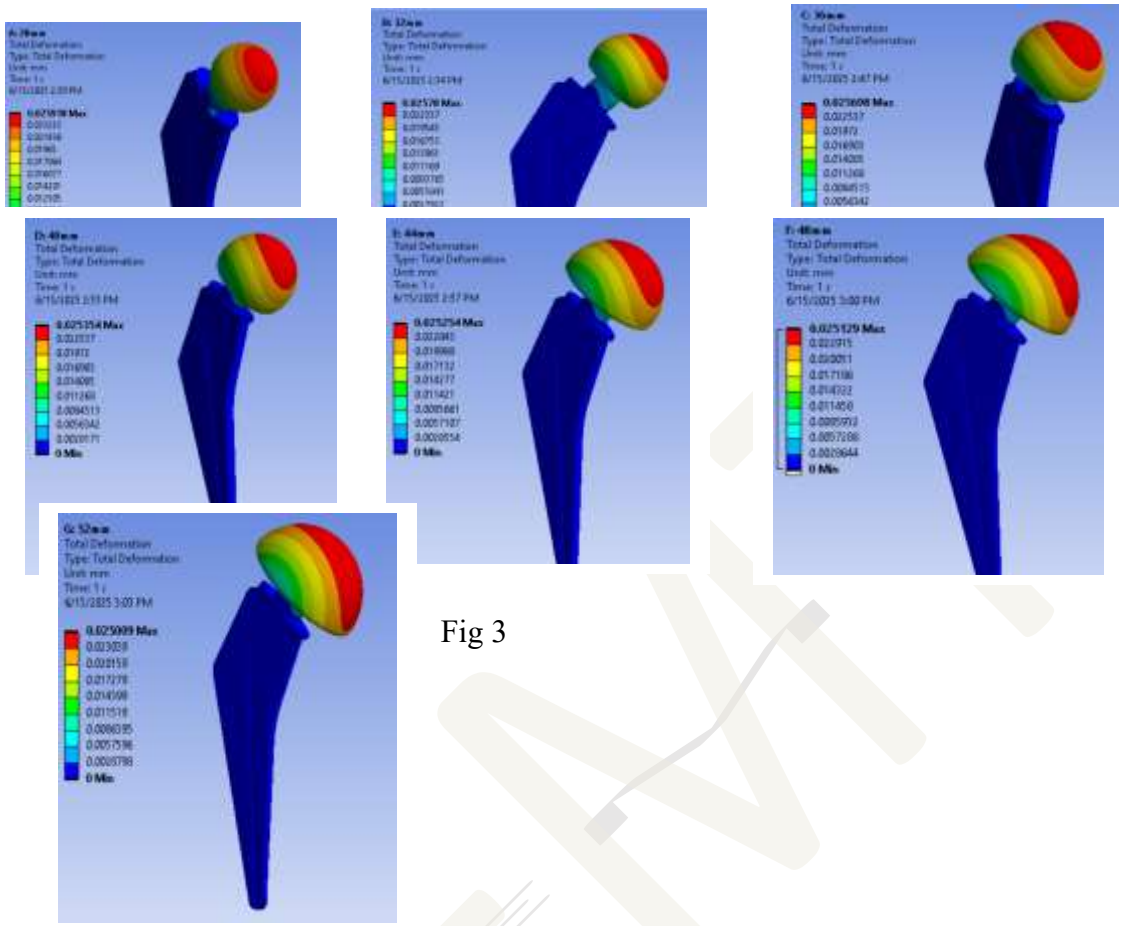


Fig 3

According to the FEA results displayed above, the deformations (displacements) decrease in proportion to the femoral head diameters. The 28 mm femoral head diameter registered the highest deformation, measuring 0.025918mm, while the 52 mm diameter showed the lowest deformation, at 0.025009mm. According to published research, as femoral head diameter increases, deformation levels fall, and stability is enhanced, respectively [6].

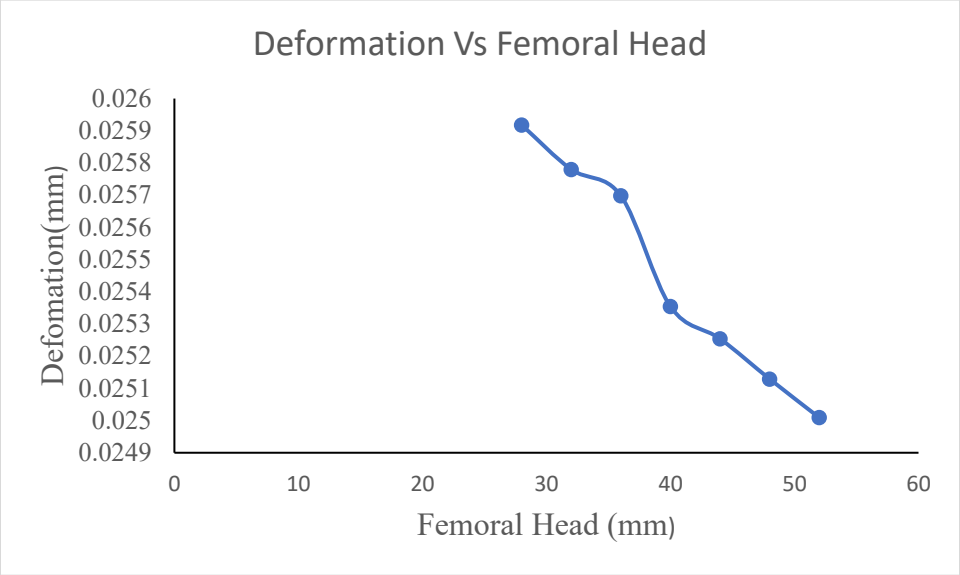


Figure 4: Graph of Deformation Femoral Head

Figure 4: Visually represents the relationship between deformation and varying femoral head diameters. To further investigate these findings, the data presented in Table 3 underwent subsequent statistical analysis utilising SPSS software (version 23). This analysis aimed to ascertain the level of statistical significance and characterise the association between different femoral head diameters and their corresponding deformation. Specifically, deformation, designated as the dependent variable, was regressed against femoral head diameter, which served as the independent (predictor) variable. The resultant findings obtained from the SPSS software (version 23) are presented in the following

Table 4: Shows the Model Summary for Deformation and Femoral Heads

Model	$\dot{R}$	R^2	$Adj\ R^2$	Std Error of the Estimates	Durbin Watson
1	0.986	0.973	0.967	0.00063263	2.340

Source: SPSS output 2025.

The computed correlation coefficient of 0.986 indicates a substantial, positive linear relationship between the predictor variable (femoral head diameter) and the response variable (deformation). This value signifies that the relationship between these two measures is exceptionally strong, closely approaching a perfect linear correspondence. Furthermore, the coefficient of determination (R-squared) was computed at 0.973, or 97.3%. This considerable finding demonstrates that 97.3% of the overall variation within the dependent variable is statistically attributable to the independent variable.

Table 5: Shows the ANOVA for Deformation and Femoral Heads

Model		Sum of Squares	df	Mean Square	F	Sig
1	Regression	0.000	1	0.000	178.541	0.000
	Residual	0.000	5	0.000		
	Total	0.000	6			

Source: SPSS output 2025

The ANOVA table furnishes an assessment of the model's overall utility by determining its statistical significance. Specifically, it ascertains whether a model employing a single explanatory variable demonstrates a significantly improved fit compared to a baseline model utilising only the grand mean. Given that the p-value (0.00) is considerably below the predetermined critical value ($\alpha = 0.05$), this indicates that the model, incorporating a single predictor, exhibits a statistically significant capacity to predict the dependent variable 'deformation'. This further implies the presence of a statistically significant linear association between the independent and dependent variables, thereby validating the effectiveness of the linear model.

Table 6: Shows the Coefficients for Deformation and Femoral Heads

Model	Unstandardized Coefficient β	Sig
	0.027	0.000
(Constant)	-0.00003994	0.000
Femoral_Head_Diameter		

Source: SPSS Output 2025

Table 6: illustrates the functional principles governing the model's operation.

$$y_0 = \beta_0 + \beta_1 x_1 + \cdots + \epsilon \quad (1)$$

This implies that

$$y_0 = 0.027 - 0.00003994 x_1 + \epsilon \quad (2)$$

The established model indicates that an increment of one millimetre in femoral head diameter correlates with a notable decrease in the deformation encountered by the acetabular cup element of the hip implant. This phenomenon augments joint stability by extending the 'jump distance' necessary to initiate dislocation. Consequently, this mechanism contributes to a diminished probability of revision surgical intervention stemming from dislocation, quantified by a reduction of approximately 0.00003994 mm.

5. Conclusion

A Finite Element Analysis (FEA) was conducted for a homogeneous material, specifically Ti-6Al-4V, in the present study. This alloy is extensively utilized in hip implants due to its outstanding biomechanical characteristics. For the analysis, a prosthetic stem with a trapezoidal cross-section was employed, featuring femoral head diameters varying from 28 mm to 52 mm. Throughout the investigation, the dimensions of the acetabular cup and its backing were kept constant. Loading

and boundary conditions were applied in accordance with established ASTM guidelines. The FEA results indicated that the deformations decreased proportionally with increasing femoral head diameters. The highest deformation, recorded at 0.025918mm, was associated with the 28mm femoral head diameter, while the lowest deformation, 0.025009mm, corresponded to the 52 mm femoral head diameter.

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