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Evaluation of Stability between Conventional Femoral Stem and Short Stem in Total Hip Arthroplasty

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Abstract

Abstract Total Hip Arthroplasty (THA) is a surgical procedure that involves replacing a damaged or diseased hip joint with an artificial implant. This study focused on the design aspect of the femoral stem to enhance implant stability, a critical factor in the success of THA. The primary objectives of this research are threefold: firstly, to design different types of design using Solidwork. Next, to perform a simulation of stability analysis using Abaqus software; and thirdly, to evaluate on the assessment of stability at the bone-implant interface. The analysis in Abaqus software involves a comprehensive simulation of the mechanical behavior of the femoral stem under normal walking conditions. In this study, the factors such as material properties, load distribution, and contact mechanics at the bone-implant interface has been evaluated. Finite element analysis (FEA) has been implements to exam the displacement of the implant. The simulation results show that the conventional stem provides more stability, while the shorter stem provides less stability, with the collarless option positioned between the conventional and short stem. This shows that the stem design has a significant impact on the stability of the bone-implant interface. The study emphasizes that the stability of the bone-implant interface is a key determinant in the success of THA. In summary, the various designs of femoral stems significantly affect the stability of the implant. This study emphasizes the vital importance of femoral stem design in shaping and impacting the overall stability of the bone implant.

1. Introduction

Total hip arthroplasty, commonly called hip replacement surgery, is a surgical intervention utilized for the reconstruction of a damaged, diseased, or rigid hip joint. This procedure is employed in the treatment of various adult hip conditions such as osteoarthritis, inflammatory arthritides, avascular necrosis, post-traumatic degenerative joint disease, congenital hip disease, oncologic bone disease, and hip joint infections. The evolution of surgical techniques for hip joint disorders has progressed from early excisional arthroplasty in 1821 to the contemporary THA. In the late 1960s, significant advancements were made by Sir John Charnley through the combination of stainless-steel femoral component and a polyethylene socket fixed with polymethyl methacrylate cement [1]. Approach for improving THA has been utilising larger femoral heads, which increase range of motion and reduce the danger of impingement. Furthermore, the evolution of modern bearing couples has been critical in minimising the higher wear associated with bigger heads [2]. Furthermore, dual mobility bearings have emerged as a dependable therapy option for improving hip stability and have seen extensive use in THA for dysplastic patients and revision THA for instability [3].

Short stems have been developed especially for young patient, although they are a challenging method for initial fixation strength. Some reports on the short stem indicate that the initial fixation strength is comparable [4], although the short stem may have a higher risk of initial fixation and postoperative fracture owing to its small contact area [5]. However, there still remains uncertainty regarding the correct indications for these stems. Even companies, producing implants, have varying recommendations that are more likely based on a well-meant advice than on statistically evaluated data. Thus, it is important to evaluate the advantages and disadvantages of a short stem prosthesis [6].

Regardless of the positive outcomes of conventional cementless femoral stems, which have been shown to improve pain and function while also achieving high survival rates over 20 years, there are still several limitations, including mismatch between proximal and distal bone anatomy, non-optimal load transfer, bone loss, thigh pain, and the risk of periprosthetic fracture. Short cementless femoral stems are intended to conserve more of the patient's natural bone while also improving proximal load transmission. Although this is not a new notion, short stems are becoming more popular among younger patients [7]. As this study indicates, it is essential to prioritise stability in hip arthroplasty. Preserving primary stability of the hip stem can successfully avoid the formation of a fibrous layer at the bone-prosthesis interface while simultaneously improving bone growth in and around the prosthesis [8].
The objective of this study is to design various types of femoral stems using CAD software based on the size of the femur bone and analyze the stability at the bone-implant interface in hip arthroplasty using the Finite Element Method for each design. To achieve this goal, different geometries of the femoral stem are designed to simulate displacement using Abaqus software. A femoral stem with a larger femoral head, a hole in the bone to allow for bone growth, and a neck may be more stable, enhancing performance through simulation [9]. The expected outcome of this study is to evaluate the stability design of both conventional and short stems for hip replacement.

2. Materials and Method

The Finite Element Method (FEM) is a numerical technique employed to obtain solutions for both linear and nonlinear transient engineering issues [10]. Furthermore, FEM can be applied to anticipate the potential behavior and failure of physical systems within a virtual environment [11]. In this study Finite Element is used to analyse the assembly design of the hip implant with the femur bone. The ABAQUS software is used to simulate this assembly. This software enables for the precise illustration of the implant and bone interface, taking into account parameters such as material qualities, load distribution, and displacement. The performance of the combined implant and femur bone can be fully analysed and optimised by using FEM with the ABAQUS software.

2.1 Material Properties

There are several materials used in hip arthroplasty; based on the findings of the study carried out by the previous study, the Co-Cr Alloy has been identified as a suitable alternative to traditional metals [9]. In this study, all components of the hip implant were considered to be elastic and isotropic. Table 1 contains details on the mechanical characteristics of the Co-CR alloy and the femur bone.

Table 1 *Mechanical properties between femur bone and the Cobalt Chromium alloy.*

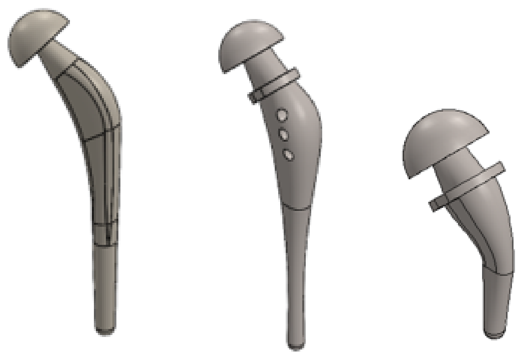
Material	Density (g/cm^3)	Elastic modulus (GPa)	Poisson ratio (v)
Cortical bone	2	17	0.3
Co-Cr Alloy	8.5	200	0.29

2.2 Development of the Three-Dimensional Bone and Femoral Stem

To study the stability of the hip stem in total hip arthroplasty, a three-dimensional model of the femur bone was created using a computer tomography (CT) dataset obtained from a male patient. By using the AMIRA software, the 2D CT dataset was automatically segmented and compile to generate a 3D triangle surface. Figure 1 shows the 3D solid model of the femoral bone [12].

Fig. 1 *Three-dimensional of Femoral Bone*

When designing a femoral stem, it is important to take into account various geometric features, such as the angleformed by the femoral neck and shaft, and the length of the femoral head offset [13]. Figure 1 shows three design of femoral stem models. In order to fit in the hip joint, the head diameter varies from 22 mm to 45 mm, according to research by Charnley et al. and McKnee et al. Additionally, the neck's diameter and length may vary between 38.5 mm for standard offset and 43.2 mm for high offset, respectively. The neck-shaft angle of the hip implant varies between 135 and 145 degrees, while the intramedullary stem's length is between 120and 180mm. Figure 2 shows the three different designs of femoral stem used in this study. For the first design, Figure 2(a), it is cylindrical with collarless stem. While for the second design Figure 1(b), a collar has been added at the neck of the stem. At the same time, holes have been included at the proximal part to enhance the stability of the stem. For the third design, in order to study the effect of stem length on the stability, a short stem has been developed as shown in Figure 1(c).



a) (b) (c)

Fig. 2 *Designs of the femoral stem (a) Collarless Stem (b) Conventional Stem (c) Short Stem*

2.3 Finite Element Analysis

Finite element analysis was implemented to simulate the performance of the hip implant for THA. The initial stage involved utilizing CAD software to create a three-dimensional model of both the bone and hip implant. An assembly process was carried out to merge the bone and implant together. Once the assembly was completed, the merged part was exported from SolidWorks and imported into Abaqus Software for further analysis. After that, the material properties for each part of the geometric models were defined. The value constraints and load conditions were specified for both the bone and hip implant. To effectively represent the behavior of the design, a mesh was constructed for the geometric models in Abaqus, and contact interactions between the bone and hip implant were properly characterized. Finally, the stability was examined to evaluate its performance. Figure 3 shows the contact forces applied to human bones, and Table 2 outlines the magnitudes of these forces during normal walking conditions. Under normal walking conditions, the femoral bone experiences four different types of forces: joint contact force, abductor force, tensor fascia latac force, and vastus lateralis force. The simulations is considered as static analysis.

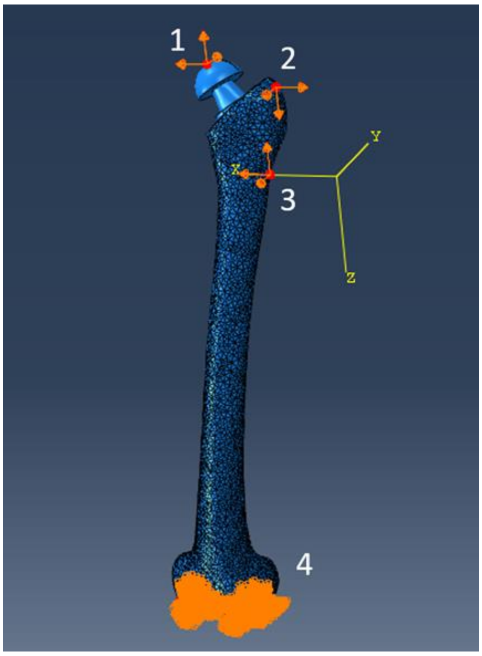


Fig. 3 *Point of forces contacting the bone*

Table 2 *Load and boundary condition*

Force	Point	Fx (N)	Fy (N)	Fz (N)
Joint Contact Force	1	433.8	263.8	-1814
Hip Abductors	2	-465.9	34.5	-695
Vastus Lateralis	3	-7.2	148.6	-746.3
Boundary Condition	4	0	0	0

3. Result and Discussion

In this study, the hip stem's stability at the implant-bone interface was assessed by examining the magnitude of relative displacement. Relative displacement, in this context, gauges stem stability by analysing displacement nodes on the stem in relation to the femoral bone node. This term indicates the extent of displacement along the x, y, and z axes. A decrease in relative displacement implies an increase in stem stability. The assessment of hip stem displacement considers both lateral and medial directions. Additionally, the study aims to identify differences in relative displacement patterns between conventional and short stems in hip arthroplasty. To ensure good stability between the hip stem and bone, the tolerable micromotion for implant osseointegration should be less than 40µm to encourage bone in-growth [14]. The relative displacement results were recorded through nodes that were selected on the surface of the hip stem. Figure 4 shows the selection of nodes on the stem's surface, specifically along the lateral and medial pathways. Sequence nodes has been selected along the medial path and lateral path.

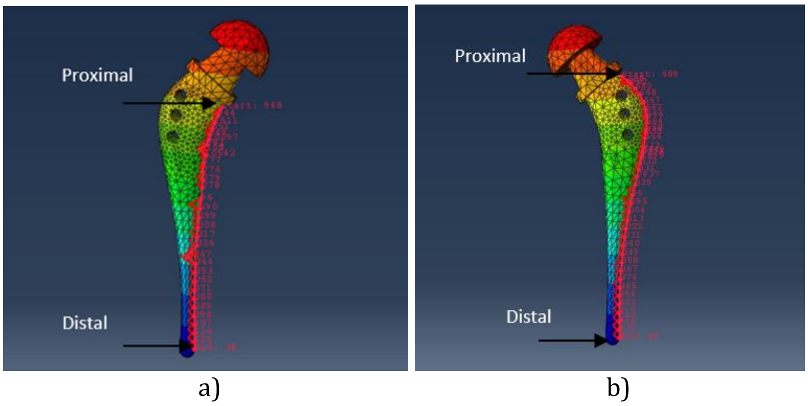


Fig. 4 *(a) Medial path and (b) lateral path on the hip stem*

Figure 5 illustrates the graph comparison displacement between conventional, short and collarless hip stem along medial path. The highest value for the displacement is short stem with 5.4 µm following by collarless stem with 5.3 µm and conventional stem with the lowest displacement which are 2.8 µm. The graph illustrates that the displacement along the medial path between the short stem and collarless stem is comparable, with no significant difference observed.

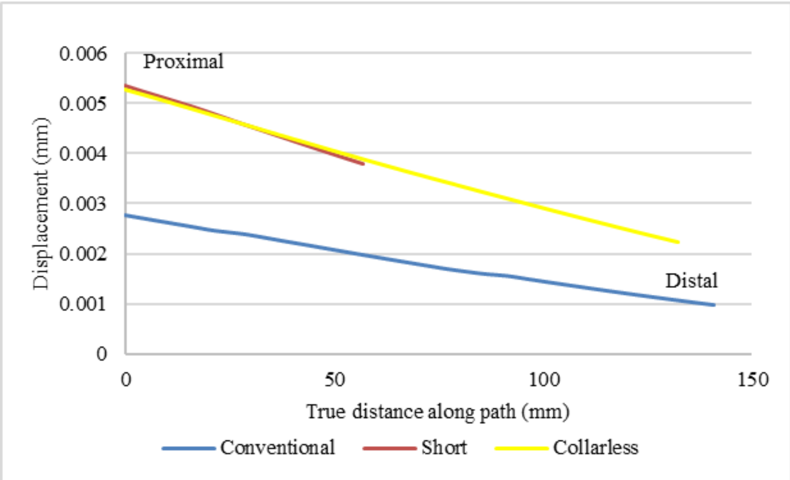


Fig. 5 *Comparison displacement graph between conventional, short, and collarless stem on medial path*

Figure 6, Table 3 and Table 4 show the comparison displacement between conventional, short and collarless hip stem along lateral path. The highest value for the displacement is short stem with 5.7 µm following by collarless stem with 4.7 µm and conventional stem with the lowest displacement which are 3.0 µm. Previous research has shown that collared stems show higher rotational and vertical stabilities than collarless stems. Collared stems are also more resistant to periprosthetic fractures, based on mechanical testing. As for the graph, it shows significant difference between the hip stems along the lateral path.

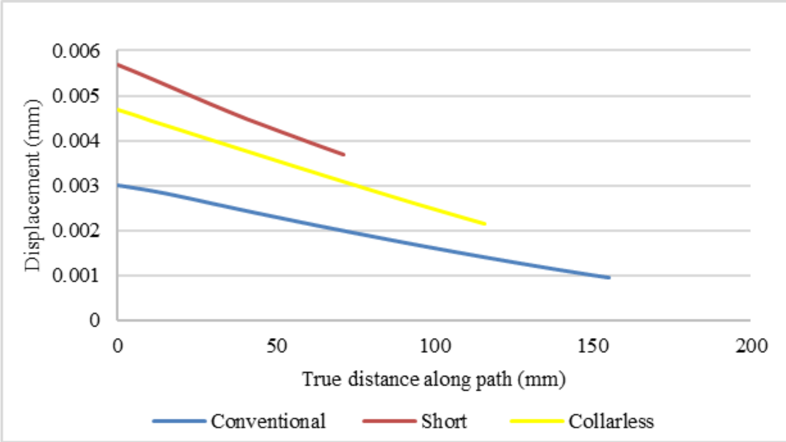


Fig. 6 *Comparison displacement graph between conventional, short, and collarless stem on lateral path*

Table 3 Highest value displacement on each of all design

	Conventional Stem	Short Stem	Collarless Stem
Medial Displacement (μm)	2.8 μm	5.4 μm	5.3 μm
Lateral Displacement (μm)	3.0 μm	5.7 μm	4.7 μm

Table 4 Lowest value displacement on each of all design

	Conventional Stem	Short Stem	Collarless Stem
Medial Displacement (μm)	1.0 μm	3.8 μm	2.2 μm
Lateral Displacement (μm)	1.0 μm	3.7 μm	2.2 μm

4. Conclusion

Stability of hip stem is one the main factor leads to the successful of hip arthroplasty. In this study, three distinct designs which are conventional stem, short stem, and cementless stem were design based on femur bone size Subsequently, finite element analysis was performed using ABAQUS software to analyse the stability at the bone-implant interface in hip arthroplasty. Through the simulation of this study, the result for the stability at the bone-implant interface for the conventional stem, short stem and cementless stem able to determine. The bone-implant interface analysis focuses on normal walking conditions. Simulation results reveal that the conventional stem is the most stable, displaying the lowest displacement compared to the short and cementless stems. This is attributed to the conventional stem's design, featuring a larger femoral head, neck, and a well-designed hole, promoting bone growth and enhancing overall stability. The short stem, despite its lower stability at the interface, still falls within the acceptable range for osseointegration, making it a viable choice for total hip arthroplasty (THA). The collarless stem, designed for simplicity and bone preservation, falls in between in terms of stability. In summary, the conventional stem is the most stable, followed by the cementless and short stems, all within the acceptable range which are lower than 40μm for osseointegration affirming their potential use in total hip replacement.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Syahrul, Haslina Abdullah****; data collection****: Muhammad Syahrul****; analysis and interpretation of results:*** *Muhammad Syahrul, Haslina Abdullah****; draft manuscript preparation:*** *Muhammad Syahrul, Haslina Abdullah. All authors reviewed the results and approved the final version of the manuscript.*

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