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Contact pressure analysis of acetabular cup surface with dimple addition on total hip arthroplasty using finite element method

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Abstract. This research aims to analyze the contact pressure on acetabular cup surface with dimple addition and without dimple addition. The main contribution in this research is to explore the influence of dimple addition to contact pressure that affects implant lifetime. The simulation is carried out by giving fully 3D physiological loading of the hip joint under normal walking conditions. Contact pressure analysis conducted on dry contact condition and meshing with the two-pole method performed to provide a comprehensive contact pressure result. The results show that the total hip arthroplasty model with dimple addition can reduce contact pressure for all phases in one full cycle with average decreased by 15.53% which indicates that adding dimple to the contact surface in the total hip arthroplasty bearing can extend the life of implant use.

Keywords: total hip arthroplasty, contact pressure, surface, dimple, finite element method

1. Introduction

Widely known diseases of the human hip joint such as osteoarthritis and avascular necrosis which cause cartilage degradation [1] and femoral neck fracture due to a specific event [2]. This requires recovery surgery by performing hip joint replacement surgery using an artificial hip joint with hip resurfacing or total hip arthroplasty [3]. It is known that total hip replacement surgery is one of the most operation successfully and cost effectively methods for replace hip joints to relieve pain and stabilize mobility. Hip joint replacement surgery registers approximately one million operation of hip joint replacements performed every year around the world [4] and more than 5 million artificial hip joint components are installed worldwide [5].



Contact mechanics is a branch of science from Tribology that is used to analyze contacts that occur on two surfaces that move relative to other surfaces [6], where one of the parameters is used into account in contact mechanics is contact pressure that occurs on the contact surface [7]. Components of total hip arthroplasty, which are acetabular cup and femoral head come into contact with each other in carrying out various activities done by humans [8]. Contact pressure analysis is important to do with total hip arthroplasty especially on the acetabular cup and femoral head to know the contact pressure that occurs and can be a reference to optimize the design of implants, material, parameters of surgery, and provide a preferable understanding of the long period of time performance and success of implant [9–11]. By reducing the contact pressure, we can minimize the wear on total hip arthroplasty and this has a significant effect on survival period of implant [11].

The use of textured surfaces has received special attention in application to mechanical components [12] such as trust bearings [13], roller bearings [14], journal bearings [15], piston rings [16], mechanical seals [17], cutting tools [18] also various other uses. In the field of Biomedical Engineering, particularly orthopedic implant, application of surface texturing in total hip implant has begun to carried out on the direct surface contact with the addition of dimple [19]. Based on the available literature, dimple reduces the surface contact area which decreases adhesion wear [20] and friction coefficient [21]. The addition of dimple also serves to trap worn particles, thus preventing abrasive wear from contact surfaces by third-party hard particles [22] as well as producing hydrodynamic pressure to serve additional lift [23]. Various studies have also shown the positive effect of adding dimple to bearing which can improve tribological performance proven theoretical and experimental [24]. But until now, the effect of adding dimple to contact pressure on total hip arthroplasty has not provided a more detailed description in the explanation from previous researchers.

Finite element method as an accurate computational tool for contact pressure analysis is reported to have extensively used by previous researchers to cut high costs and minimize long periods of time for trials and laboratory studies. But with the advantages offered, there are still many researchers who use finite element method with simplified models and loading. Looking at previous studies on total hip arthroplasty, Basri *et al.* [19,25] analyzed the influence of geometry and arrangement variations on dimple addition to lubrication performance using the finite element method, but the study did not focus on the analysis of contact pressures and the finite element model presented was very simplified and the force applied was still using 2D loads that did not meet the physiological conditions of the hip joint. Besides that Shankar *et al.* [26] predicting contact pressure and wear by using gait loading is not simplified, but the addition of dimple and its effect has not been done and a simple axisymmetric finite element model is used which can minimize the accuracy of the results obtained.

Research in this paper aims to analyze contact pressure on the acetabular cup surface with and without the addition of dimple. This is done by 3D dry contact models using un-simplified loading for more accurate results. Comparison of contact pressure prediction for total hip implant with and without the addition of dimple will give detail description and the development of 3D finite element model for total hip implant with the addition of dimple has been done by the authors as a novelty in this study, because there are no researchers who have succeeded in making a finite element analysis for total hip arthroplasty with the addition of dimple which has several numbers of dimple in 3D models.

2. Materials and method

2.1 Geometry and material parameter

In this research, the geometry of total hip implant, for femoral head and acetabular cup components, refers to previous studies conducted by Uddin and Zhang [27] and Mak *et al.* [9] which are described in Table 1. Table 2 show the addition of dimple to total hip arthroplasty was referred in previous research conducted by Choudhury *et al.* [28]. The combination of materials

used for femoral heads and acetabular cups is metal on metal (MoM) using Cobalt-Chromium-Molybdenum (CoCrMo) which is assumed to be homogeneous based on Ammarullah, 2019 [29]. The material properties of CoCrMo are described in Table 3. Friction coefficient in this study uses a value of 0.15. This is based on the research explanation by Bergmann et al. [30] which explains the friction coefficient for MoM bearings is in the range of 0.1 - 0.2.

Table 1. THA geometry parameter

Parameter	Size
Diameter of femoral head (R_{head})	28 mm
Clearance (c)	5 μm
Thickness of acetabular cup (t_{cup})	5 mm

Table 2. THA addition dimple parameter

Parameter	Size
Diameter	0.26 mm
Deep	0,03 mm
Shape	Circle
Pattern	Circular
Number of patterns	6
Number of dimples	91
Pitch	0,48857348 mm
Addition area	femoral head contact surface

Table 3. Material property of CoCrMo

Parameter	Size
Poisson ratio (ν)	0.3
Density (ρ)	8300 kg/m^3
Young modulus (E)	210 GPA

2.2 Geometry modelling

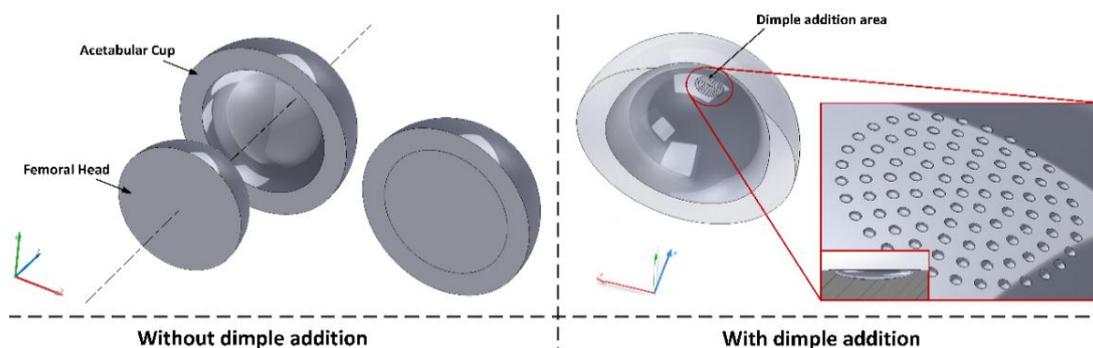


Figure 1. Geometry models without and with the dimple addition

Based on data on the geometry parameters of total hip arthroplasty in Table 1 and the dimple addition parameter of Table 2, the model of total hip arthroplasty with and without addition of dimple was made which is described in Figure 1.

2.3 Finite element modelling

The simulation is represented by acetabular cup and femoral head as main components in the research to reducing the simulation time and using less storage space. Finite element model of total hip implant is using a 3D model of ball-in-socket with femoral head asymmetries from previous study [27,31,32] for geometric efficiency that is not needed but still gives promising results.

Meshing in this study was carried out by forming dual-poled as carried out by Pedersen et al. [33]. Micro finite element development carried out with finite element model in this study because the addition of dimple area with micro-size and large amounts on the contact surface of the femoral head is presented. This is imperative to considering the automatic meshing in cases like this is difficult to do, and no researchers have presented their finite element analysis for total hip implant cases with the addition of micro-sized dimple and large amounts and can make contact nodes that meet each other between two surfaces. The application of element boundary area in dimple addition area has further improved so that it can mesh the dimple addition area, but does not change other contact nodes. Meshing in areas with the addition of dimple The finite element model with and without the dimple addition is described in Figure 2.

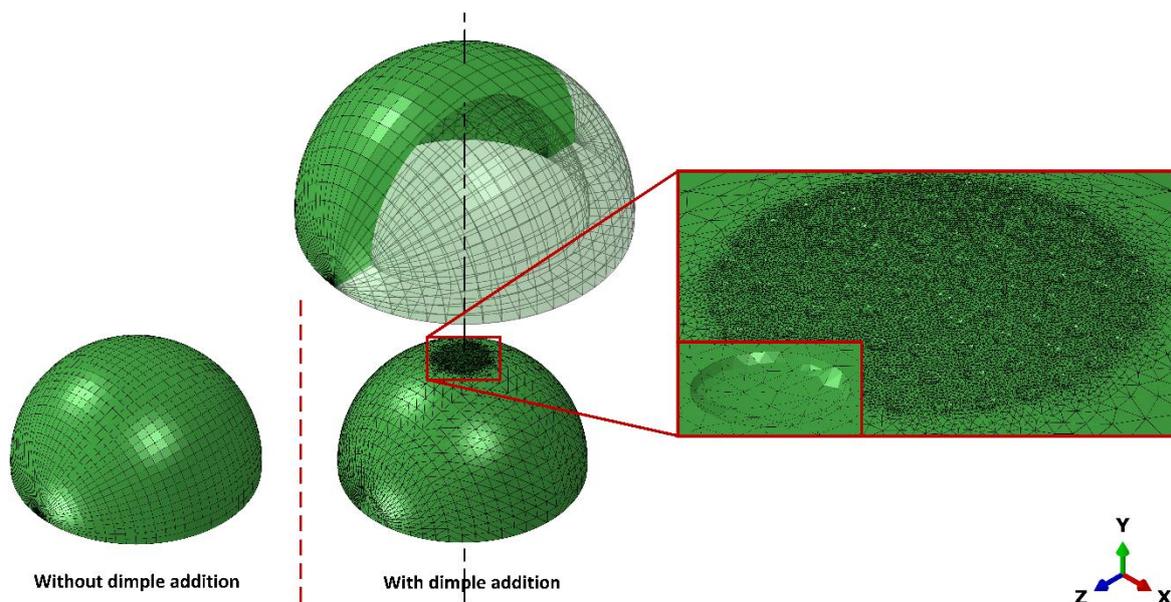


Figure 2. Finite element model without and with the dimple addition

2.4 Boundary conditions

Boundary conditions in the simulation of total hip arthroplasty are important to determine in order to simulate the object in accordance with real conditions. Boundary conditions are given to the femoral head and acetabular cup components. In acetabular cup, boundary conditions are given by making the object immovable by making fully constrained entire surface of acetabular cup based on actual conditions where acetabular cup attaches to the acetabulum and makes it immobile. The influence of the third object during the simulation is ignored. Furthermore, for determining the boundary conditions on the femoral head, range of motion is given based on the real conditions, femoral head articulating on acetabular cup surface has a range of motion that occurs in accordance with the activities carried out. Determination of boundary conditions is explained in Figure 3.

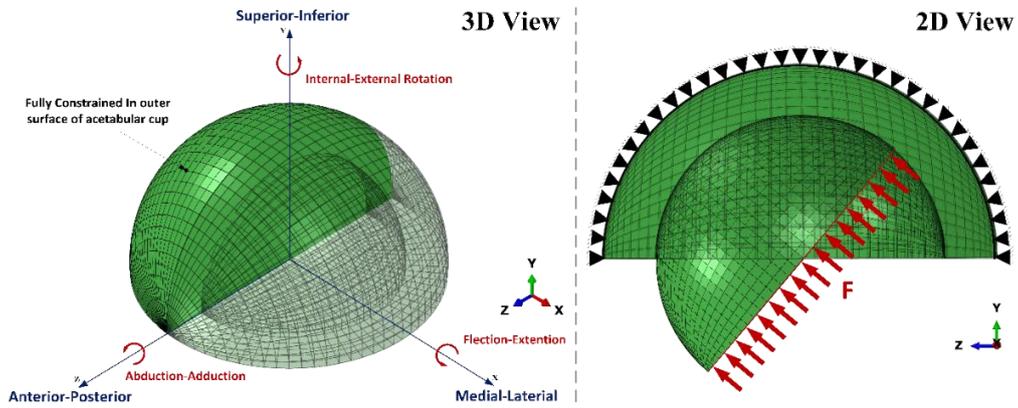


Figure 3. Determination of boundary conditions

2.5 Gait cycle

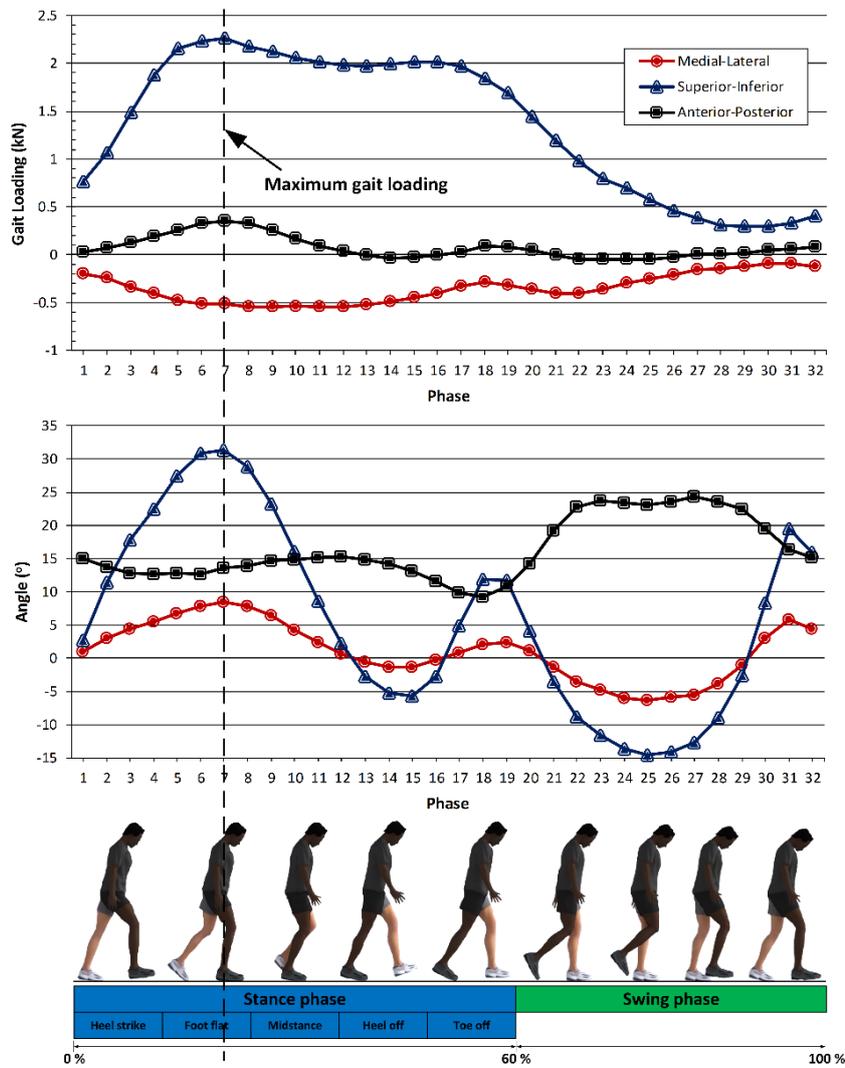


Figure 4. Gait loading and range of motion under normal walking conditions

Various studies have reported that the gait loading given in the prediction of contact pressure in total hip arthroplasty is under normal walking conditions [34]. That is because the dominant daily activities carried out by the human hip joint are in normal walking conditions. The approach taken for gait cycle under normal walking conditions with 3D loading that represents wholly physiological condition of the hip joint referring to previous studies conducted by Bergman et al. [30], where the data comes from experimental research that measures range of motion and gait loading in the left-sided hip joint using total hip implants based on a median of four different patients. Gait loading and range of motion under normal walking conditions are described in Figure 4.

For calculation simplified, we refined this cycle to 32 phases [26,27,31,32]. The 1-19 Phase is called the standing phase (the first 60% of the gait cycle), and the 20-32 phase is called the swing phase (the last 40% of the gait cycle). The magnitude and direction of the load acting on the hip joint vary according to the phase change of the normal walking cycle, and the maximum load on the hip joint is measured at 2326 N, which occurs at the 7th phase of motion at the peak of the standing leg phase.

2.6 Contact mechanics

The main parameters of the contact mechanism that need to be determined are the contact pressure and contact area, which is indicated that the contact voltage is directly related to the wear and damage of the contact surface. [35]. In contact mechanics, the relationship between the two can be formulated, where the contact pressure (P) is the applied load (F_n) divided by the contact plane (A) in Equation (1) [36].

$$P = \frac{F_n}{A} \quad (1)$$

The greater contact area generally leads to a decrease in contact pressure. The study of contact mechanics in total hip arthroplasty is related to Biotribology where the pressure on the bearing surface is a parameter for studying overall Biotribology. Contact mechanics are important things to consider when designing total hip arthroplasty [37]. Contact pressure values in this study will be obtained through numerical analysis using the finite element method.

3. Results and discussion

3.1 Convergence study

This study was conducted to select the representative number of elements for the total finite element analysis of total hip implant in this research, namely the total hip arthroplasty model without and with the addition of dimple. The results of the convergence study without and with the addition of dimple are respectively explained in Figure 5 and Figure .

Total hip implant model with and without the addition of dimple, eight simulations were performed with a number of different elements, then one of them was chosen as a representation of the model with the optimal number of elements. For models without the addition of dimple, the results of the 4th simulation with the number of elements 23,484 were chosen as a representation of the model with the optimal number of elements because the results of the 4th to 8th simulation of this model have good linearity with maximum contact pressure values ranging from 80- 81 MPa, but the smallest number of elements is owned by the results of the 4th simulation. With good linearity in mind and the use of fewer elements, we chose the results of the 4th simulation. As for models with the addition of dimple, the highest number of elements was chosen as the representation of the model with the optimum number of elements because the addition of micro-sized dimple with a large number requires finer elements to provide accurate contact analysis simulation results. With this in mind, the results of the 8th simulation with a total of 195,251 elements for the total hip arthroplasty model with the addition of dimple were chosen as representative models.

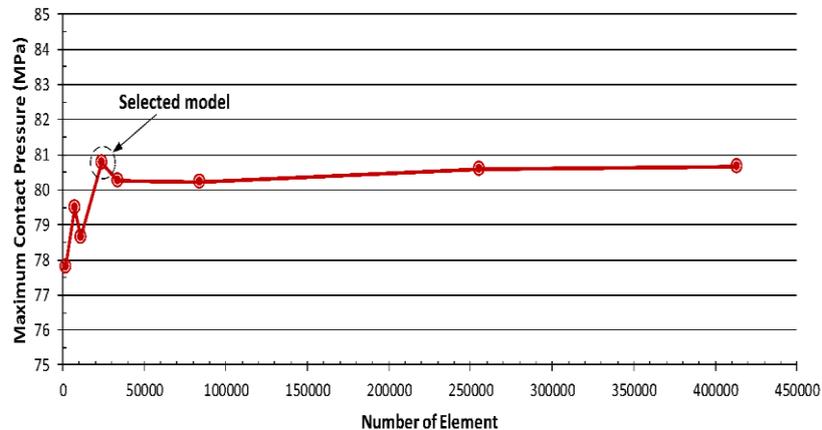


Figure 5. Convergence study of model elements without the addition of dimple

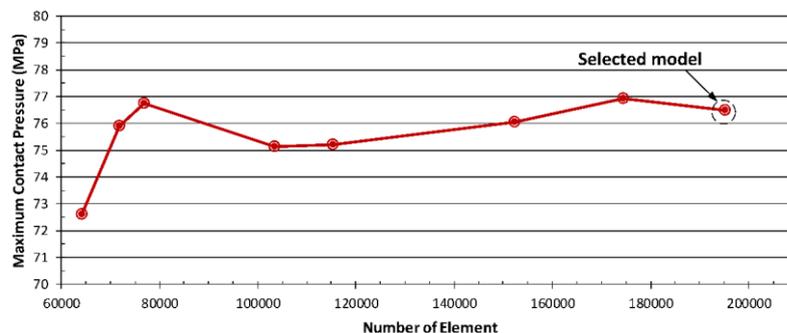


Figure 6. Convergence study of model elements with the addition of dimple

Comparison of the number of elements used in this study was carried out with previous research conducted by Uddin and Zhang [27] for the total hip implant model without the addition of dimple, while for the total hip implant model with the addition of dimple not done because it does not have research that can be used as a comparison of the number of elements. The total number of hip arthroplasty model elements without the addition of dimple used in this study was 23,494 elements, whereas in previous studies conducted by Uddin and Zhang there were 67,696 elements. The difference in the number of elements used between this study and those conducted by Uddin and Zhang is so significant, where the number of elements used by Uddin and Zhang is almost three times more than those used by the authors in this study. However, if we look at the way of meshing between this research and those conducted by Uddin and Zhang differently. The author conducts meshing by forming two axes so as to make the hexahedral element so dominant and make the contact pressure contour look so clear, whereas in research conducted by Uddin and Zhang the meshing method they use is automatic meshing so that it does not have a structured pattern and many tetrahedral elements are used.

3.2 Contact pressure validation

Contact pressure validation was carried out with research conducted by Uddin and Zhang [27] for the total hip arthroplasty model without the addition of dimple, while for the model with the addition of dimple not done because it does not have research that can be used as a validation of contact pressure. In previous studies as a contact pressure validation, the highest contact pressure value was in the 7th phase with a value of 78.57 MPa, while for the highest contact pressure value obtained by the author was in the 7th phase with a value of 80.75 MPa. The percentage of error is sought to see the suitability of the results between the two and the percentage of errors obtained is 2.7% which meets the contact pressure validation criteria with a percentage error <5% so that it

is deemed appropriate and can proceed to the contact pressure analysis stage. Contact pressure validation is explained in Figure 7.

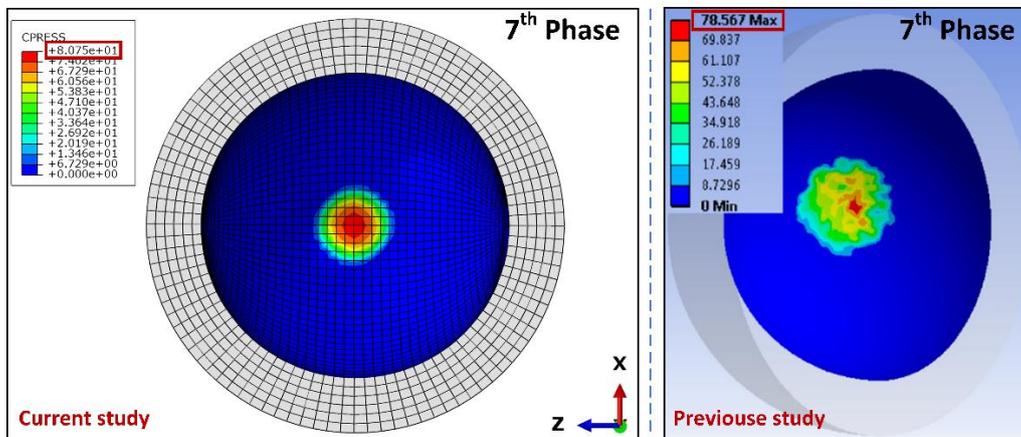


Figure 7. Contact pressure validation

The results obtained provide a rational translation because in the division of phases as much as 32 for one normal loading cycle [26,27,31,32], the biggest load is in the 7th phase which is one of the phases of the standing phase (60% cycle, phase 1-19) and if we look at the physiological condition of the hip bone connection, the 7th phase is a condition when the hip bone connection holds the body's burden completely to step the other foot, where the other foot is undergoing a phase of swing [30,38].

3.3 Contact pressure analysis

After passing through a normal loading cycle with a total of 32 phases, a contact pressure value on the acetabular cup surface is obtained in total hip implant with and without the addition of dimple. Contact pressure analysis of the two models is explained in Figure .

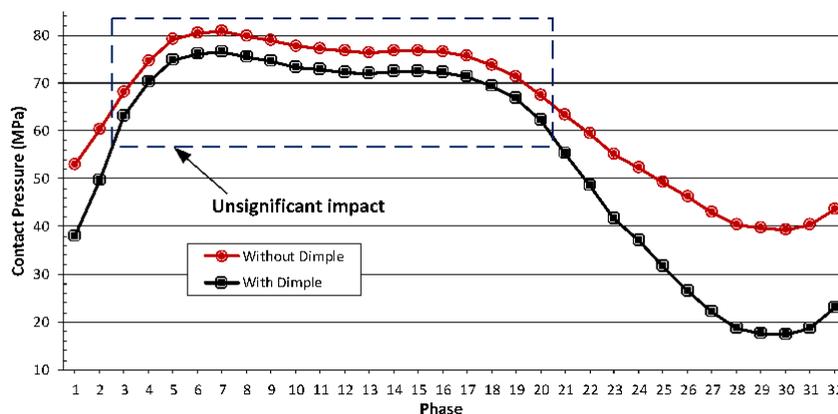


Figure 8. Contact pressure analysis

Based on Figure 8, it can be seen that the total hip arthroplasty model without the addition of dimple in one full cycle has a higher contact pressure value for all phases when compared to the total hip arthroplasty model with the addition of dimple. This illustrates that the impact of dimples on the reduction in contact pressure with the middle was reduced by 15.53%. This is because the addition of dimples to the surface of the femoral head makes the area that comes in direct contact

with the acetabular cup diminishes and expands the real surface of the femoral head to minimize the contact pressure that occurs on the acetabular cup [36].

The maximum contact pressure for the total hip implant model without and with the addition of dimple are both in the 7th phase with values of 80.75 MPa and 76.5 MPa respectively. This shows that the addition of dimple to total hip arthroplasty in this study can reduce the maximum contact pressure by 5.26 %. As for the minimum contact pressure for the total hip arthroplasty model without and with the addition of dimple both are in the 30th phase with values of 39.28 MPa and 17.3 MPa respectively. This shows that the addition of dimple to total hip arthroplasty in this study can reduce the minimum contact pressure by 55.96 %. Significant reduction with the addition of dimple can be seen in phases 1-2 and 23-32 which can reduce contact pressure more than 10 MPa in each phase. It can be concluded that the effect of dimple addition on total hip arthroplasty is very significant in swing phase and contrary in stance phase.

Contact pressure analysis in this study successfully demonstrated a reduction in contact pressure by adding dimple to the contact area. Looking at Archard's wear equation [39] where one of the factors that influence wear is contact pressure. Moreover, reducing contact pressure the wear will be reduced so that it can prolong the use of implant devices.

4. Conclusions

Research in this paper successfully carried out a finite element study for total contact pressure of hip arthroplasty without and with the addition of dimples in dry contact under 3D physiological loading conditions in a normal walking cycle. The results of this study can be concluded as follows:

- The gait cycle, intensity and location of the maximum contact pressure in the bearing component changes according to the loading phase, with the highest contact pressure value in the 7th phase in the standing phase and the lowest in the 30th phase in the swing phase.
- Adding dimple to total hip arthroplasty can reduce contact pressure in all phases in one cycle with median lower by 15.53 %.
- Through validation with previous research, it can be found that the contact pressure analysis model in this study can provide rational predictions.

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