Effect of Micro-Separations and Cup Inclination Angles influencing Contact Mechanics of PCD-PCD for Hip Resurfacing using Elevated Acetubular Cup Rim Design for Various Gait Loads

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Received: 01.10.2025 *Revised: 08.10.2025* *Accepted: 10.10.2025* *Published: 12.10.2025*

Abstract

The femur head and acetabular cup are modeled using finite element (FE) method of a hip implant to analyse the contact mechanics and failure of implants. The model is subjected to various gait activities such as carrying load, climbing ladder etc., consisting of up to 19 gait loads for the poly crystalline diamond (PCD) material. The main aim of this study is to analyse how the contact pressure, and first Principal stress affect the contact mechanism in the hip resurfacing for each gait activity for different micro-separation’s such as 0, 0.5, 1, 1.5, 2, and 2.5 mm and for various cup inclination angles such as 35°, 45°, and 55°. The results revealed that PCD had better reduction in contact pressure for 75° inclination angle when compared with other cup inclination angles.

Keywords: PCD; Hip resurfacing; Microseparation; Inclination Angle; FEA; Gait load

1 Introduction

The primary stability of acetabular cups remains a major cause of premature implant loosening. with varying wall thicknesses showed that thinner walled implants required less impaction energy, minimizing bone damage and improving stability[1]. An in vitro tribological analysis ZTA against alumina using different bio lubricants to replicate human gait activity such as walking, running, climbing ladder etc., author finds that the sesame oil perform best under different conditions [2]. Many in-vitro studies suggested that there were several parameters that affect hip implant parameters which include the head diameter, head lateral displacements analyzed using hip simulator and tribometer to estimate mass loss, friction and wear rate[3-5] An in silico wear testing method for mixed elasto-hydrodynamic lubrication (MEHL) effects to simulate hip implant wear in total hip replacement, offering a faster alternative to ISO 14242 tests [6]. Another study examined silicon nitride on alumina material under various gait loads using saline lubrication, and author finds that higher gait loads reduced friction and wear due to protective tribo film formation in the hip joint[7]. The use of elevated acetabular cup rim designs with rounded corners using finite element analysis (FEA), that shows less contact stresses when compared to conventional cup design and it improved bio mechanical performance within cobalt-chromium yield limits[8]. Commercial hip implants subjected to FEA, revealing oval cobalt-chromium offered excellent load distribution, minimal deformation, and extensive fatigue resistance[9]. Archard's law was used to approximate oval implant wear, discovering UHMWPE cups with CoCr stems had minimal deformation and Ti-6Al-4V stems kept yearly wears at 0.063 mm, verifying CoCr's excellence in wear resistance [10]. Another study revealed that resurfacing arthroplasty materials and determined that PEEK and PEEK-ATZ hybrids with PEEK had reduced stress shielding and bone atrophy compared to customary CoCr and ceramic materials, suggesting enhanced long-term bone preservation[11]. Hard-on-hard bearing polycrystalline diamond (PCD) using FEA revealed that PCD-on-PCD pairs had the lowest von Mises stress (2.47% yield strength) compared to CoCrMo and Al_2O_3, consequently emphasizing the promise of PCD as a future-bearing material with enhanced strength, wear resistance, and biocompatibility for durable hip implants[12]. Various parameters like radial clearance, micro-lateralization, and corner radius were analysed for contact and von Mises stresses in both metal-on-metal and ceramic-on-ceramic prostheses by many literatures[12-20]. All these studies revealed that FEA studies proved to be better alternative for in-vivo techniques which was found to be time consuming. The present study focuses on analyzing contact mechanics of PCD-PCD biomaterial for various gait loads ranging from normal walking to physically demanding tasks for elevated acetabular cup rim design under different cup inclination angles and micro separations.

2 Material model and Boundary Conditions

The finite element modeling of hip resurfacing is shown in fig.1.The mechanical properties such as young's modulus of PCD is 900 GPa, Coefficient of friction for PCD is 0.1, and the Poisson ratio for PCD is 0.1[21].

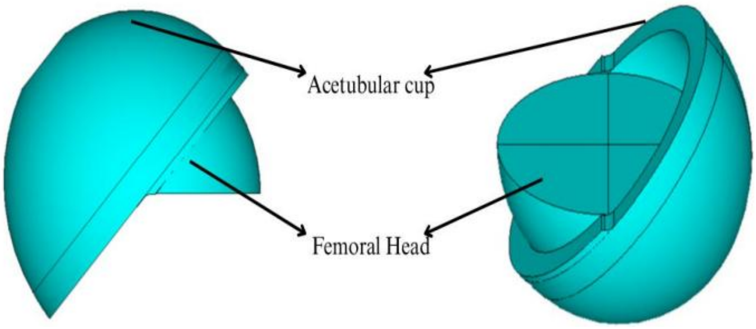

Figure.1 Elevated acetabular cup and head of hip resurfacing

The acetabular cup was constrained in all direction for zero displacements. The femoral head was applied with gait loads, therefore except y direction all other direction arrested or fixed. The various gait loads are shown in Table. 1, loading conditions corresponding to normal walking, stair ascending and descending, sitting down, and standing up were applied for hip joint loading. The meshing of model is performed using element size of 1 mm after suitable convergence study and contact between cup and head established using 3D contact and target elements of CONTA 174 and TARGE 170.

Table. 1: Gait Activity considered for present study [22, 23]

S.No.	Gait Activity	Gait Load(N)
1	Sitting down/Getting up	2753
2	Lifting 25 kg	3775
3	Stairs up	3804
4	Stairs down	3435
5	Gait/Normal walking	4003
6	Lifting 40 kg	4599
7	Carrying 25 kg	4513
8	Stairs down 25 kg	4769
9	Ladder up 70°	4173
10	Ladder up 90°	4655
11	Ladder down 70°	3917
12	Ladder down 90°	4088
13	Lifting 50 kg	5365
14	Carrying 40 kg	5479
15	Carrying 50 kg	6217
16	Load transfer 25 kg	5848
17	Stairs up 25 kg	5393
18	Load transfer 40 kg	6501
19	Load transfer 50 kg	7040

3 Result and Discussion

3.1 Contact Pressure Analysis

The maximum and minimum contact pressure are calculated for each gait load for PCD-on-PCD. The maximum contact pressure of PCD is shown in the Figure 2a and minimum contact pressure of PCD is shown in the Figure 2b. Figure 3 a & b illustrate the contact pressure developed in the acetubular cup for the material PCD for 35-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum contact pressure was developed for the 35 degree in the 0.5 mm micro-separation and it is 1304.85 MPa. The minimum contact pressure was developed for the 35 degree in the 0 mm micro-separation and it is 278.18.

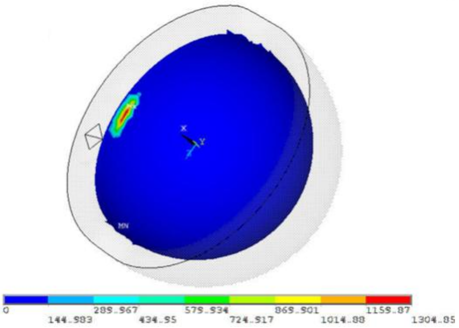

Figure 2a: Maximum Contact Pressure developed for 65° and 1mm micro-separation for PCD

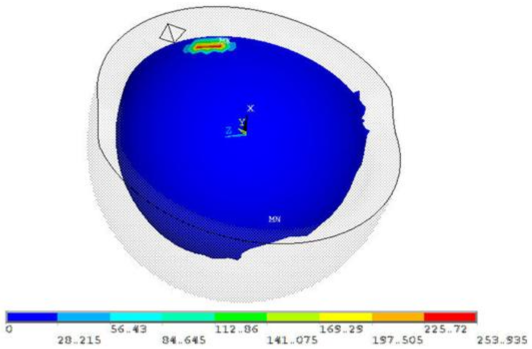

Figure 2b: Minimum Contact Pressure developed for 65° and 1mm micro-separation for PCD

Figure 3c & d illustrate the contact pressure developed in the acetubular cup for the material PCD for 45-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum contact pressure was developed for the 45 degree at 2.5 mm micro-separation and it is 972.32 MPa. The minimum contact pressure was developed for the 45 degree at 0 mm micro-separation and it is 273.83 MPa. Figure 3e and f illustrate the contact pressure developed in the acetubular cup for the material PCD for 55-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum contact pressure was developed for the 55 degree at 2.5 mm micro-separation and it is 890.59 MPa. The minimum contact pressure was developed for the 45 degree at 0 mm micro-separation and it is 288.54 MPa. Figure 3 g & h illustrate the contact pressure developed in the acetubular cup for the material PCD for 65-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum contact pressure was developed for the 65 degree at 2.5 mm micro-separation and it is 776.58 MPa. The minimum contact pressure was developed for the 65 degree at 1 mm micro-separation and it is 253.94 MPa.

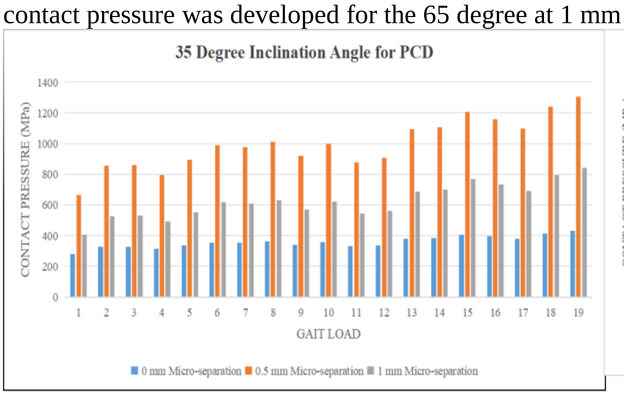

Figure 3a: Contact pressure for 0, 0.5, and 1 mm Micro-separation for PCD 35 degree

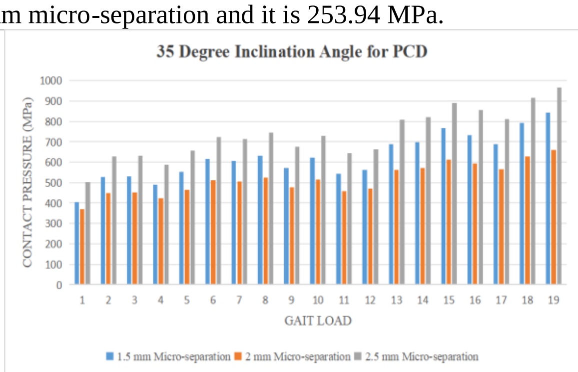

Figure 3b: Contact pressure for 1.5, 2, and 2.5 mm Micro-separation for PCD 35 degree

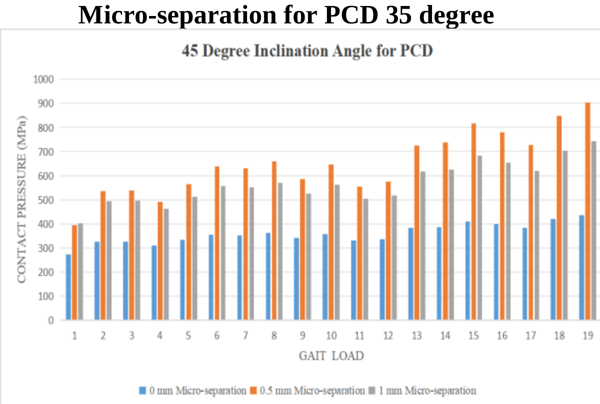

Figure 3c: Contact pressure for 0, 0.5, and 1 mm Micro-separation for PCD 45 degree

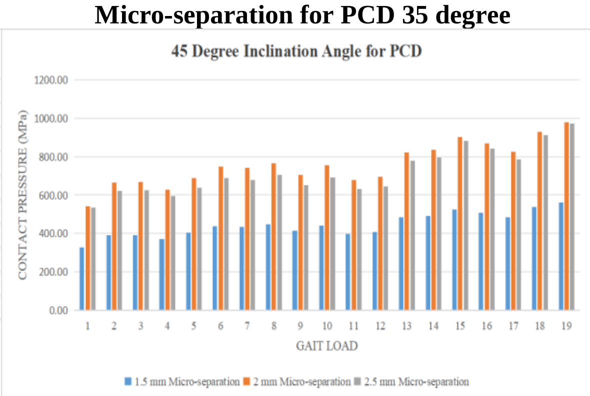

Figure 3d: Contact pressure for 1.5, 2, and 2.5 mm Micro-separation for PCD 45 degree

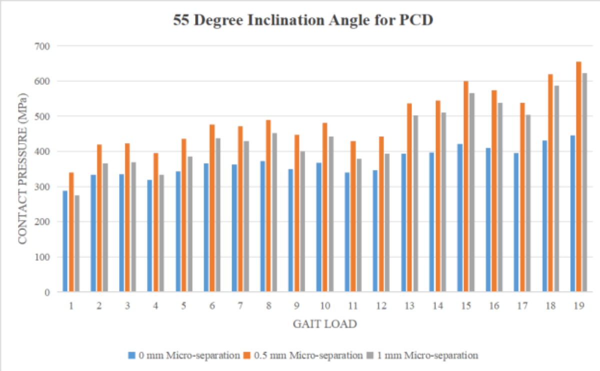

Figure 3e: Contact pressure for 0, 0.5, and 1 mm Micro-separation for PCD 55 degree

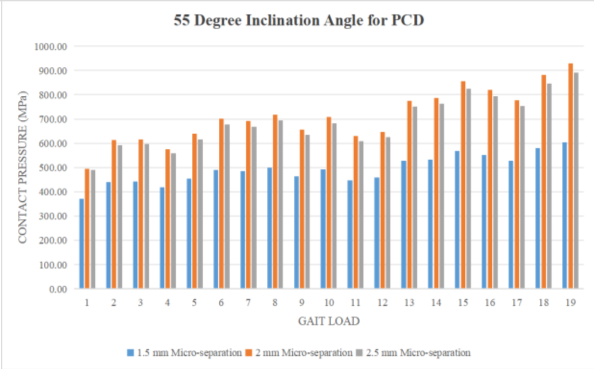

Figure 3f: Contact pressure for 1.5, 2, and 2.5 mm Micro-separation for PCD 55 degree

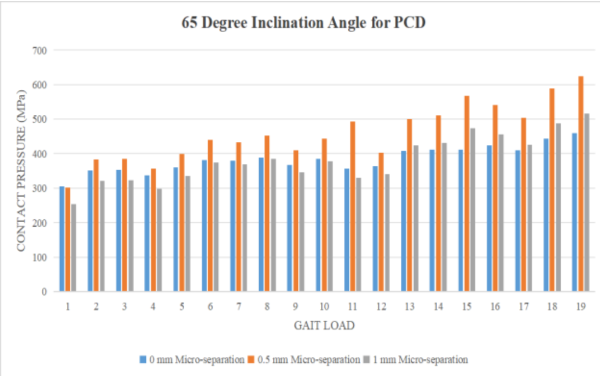

Figure 3g: Contact pressure for 0, 0.5, and 1 mm Micro-separation for PCD 65 degree

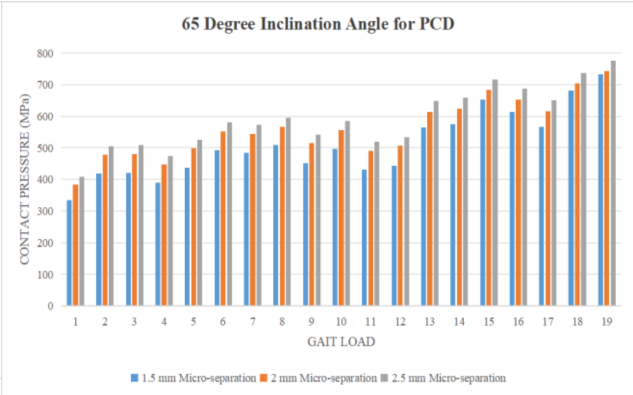

Figure 3h: Contact pressure for 1.5, 2, and 2.5 mm Micro-separation for PCD 65 degree

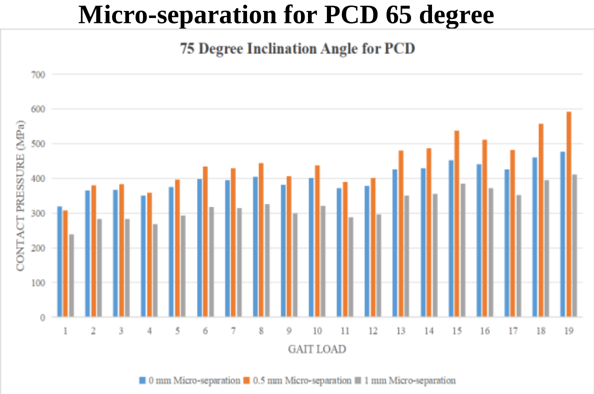

Figure 3i: Contact pressure for 0, 0.5, and 1 mm Micro-separation for PCD 75 degree

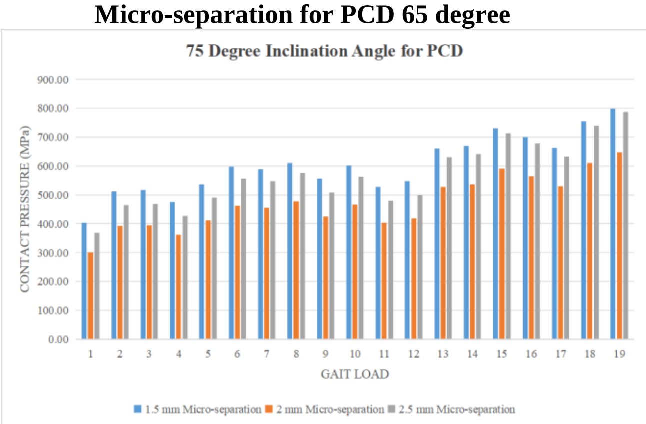

Figure 3j: Contact pressure for 1.5, 2, and 2.5 mm Micro-separation for PCD 75 degree

Figure 3 i & j illustrate the contact pressure developed in the acetubular cup for the material PCD for 75-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum contact pressure was developed for the 75 degree at 1.5 mm micro-separation and it is 798.01 MPa. The minimum contact pressure was developed for the 75 degree at 1 mm micro-separation and it is 238.50 MPa.

3.2 1st Principal Stress Analysis

The maximum and minimum 1st Principal stress is calculated for each gait load for PCD-PCD. The maximum 1st Principal stress of PCD is shown in the Figure 4a and minimum 1st Principal stress of PCD is shown in the Figure 4b.

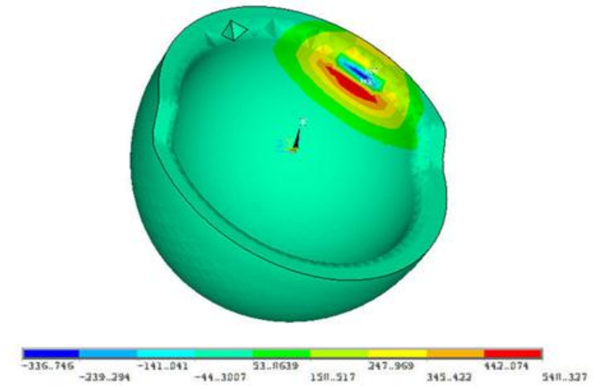	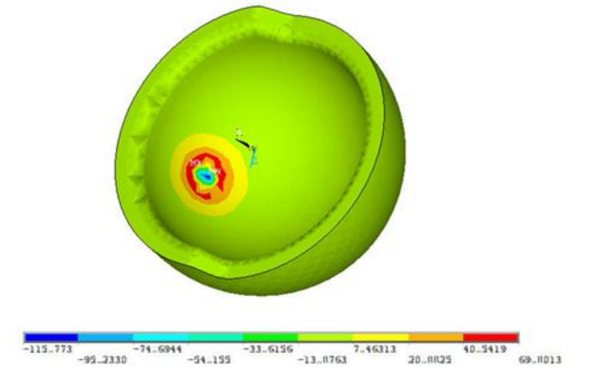
Figure 4a: Maximum1st principal stress developed for 45° and 2 mm micro-separation for PCD	**Figure 4b: Minimum1st principal stress developed for 55° and 0 mm micro-separation for PCD**

Figure 5a & b illustrate the 1st Principal stress developed in the acetubular cup for the material PCD for 35-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum 1st Principal stress was developed for the 35 degree at 2.5 mm micro-separation and it is 329.44 MPa. The minimum 1st Principal stress was developed for the 35 degree at 0 mm micro-separation and it is 67.92 MPa.

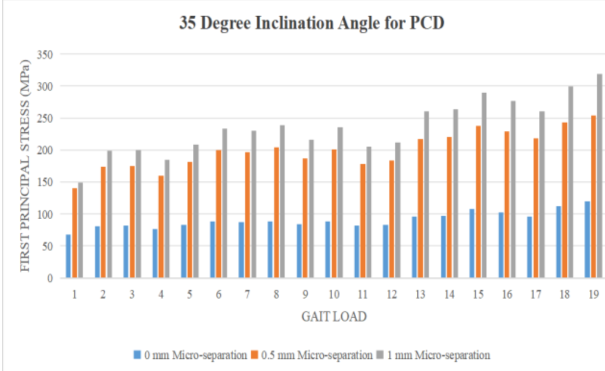

Figure 5a: 1st principal stress for 0, 0.5, and 1 mm Micro-separation for PCD 35 degree

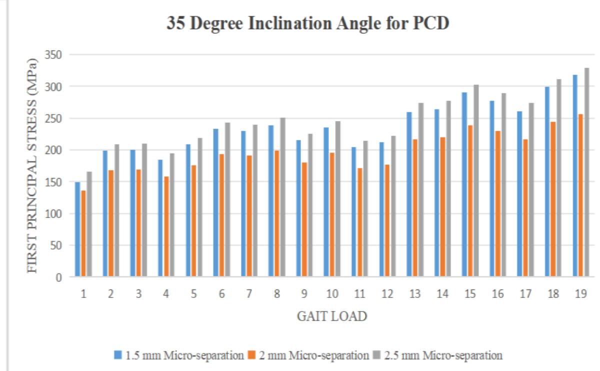

Figure 5b: 1st principal stress for 1.5, 2, and 2.5 mm Micro-separation for PCD 35 degree

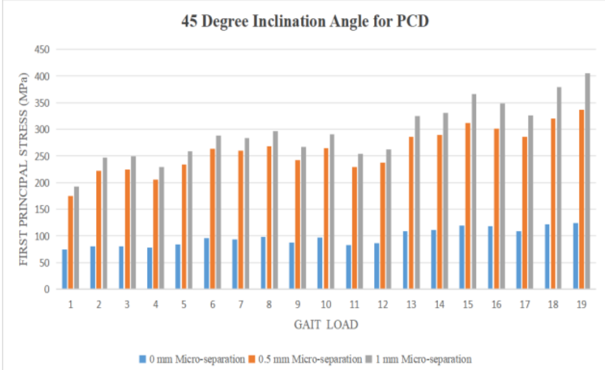

Figure 5c: 1st principal stress for 0, 0.5, and 1 mm Micro-separation for PCD 45 degree

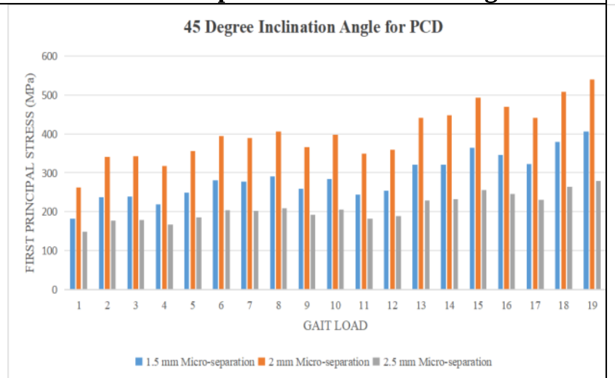

Figure 5d: 1st principal stress for 1.5, 2, and 2.5 mm Micro-separation for PCD 45 degree

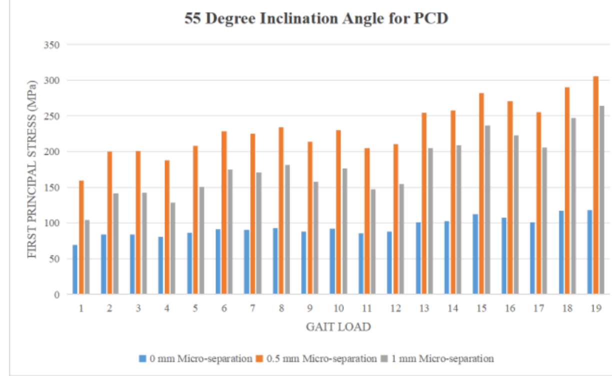

Figure 5e: 1st principal stress for 0, 0.5, and 1 mm Micro-separation for PCD 55 degree

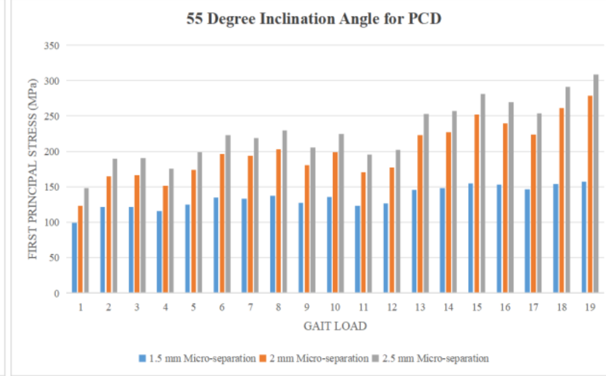

Figure 5f: 1st principal stress for 1.5, 2, and 2.5 mm Micro-separation for PCD 55 degree

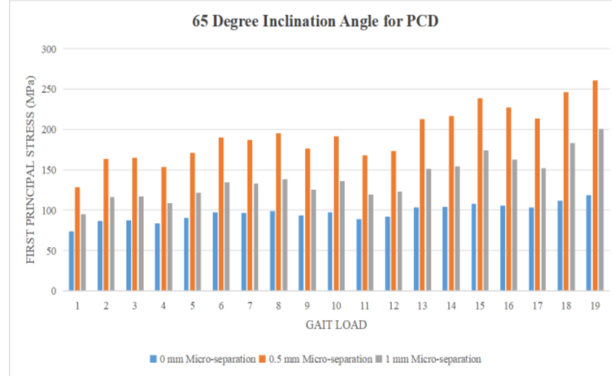

Figure 5g: 1st principal stress for 0, 0.5, and 1 mm Micro-separation for PCD 65 degree

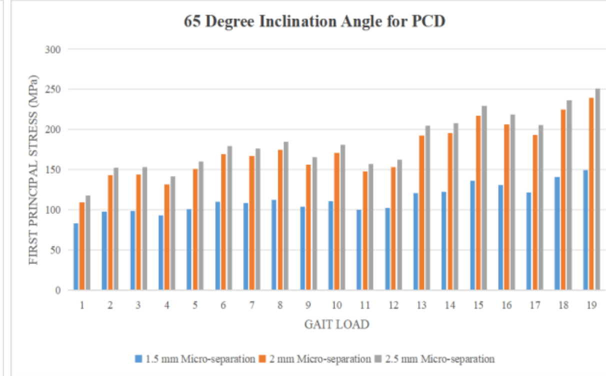

Figure 5h: 1st principal stress for 1.5, 2, and 2.5 mm Micro-separation for PCD 65 degree

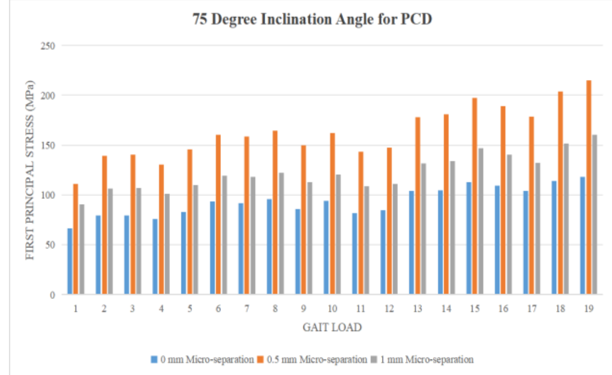

Figure 5i: 1st principal stress for 0, 0.5, and 1 mm Micro-separation for PCD 75 degree

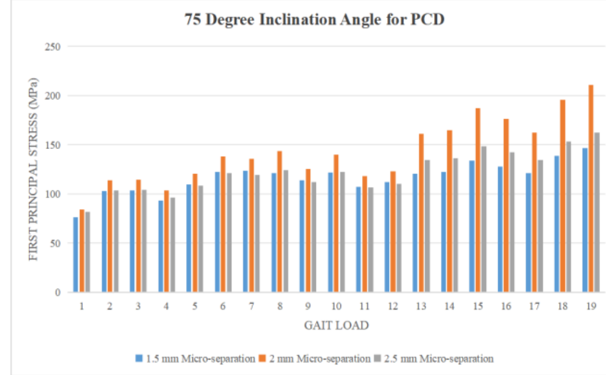

Figure 5j: 1st principal stress for 1.5, 2, and 2.5 mm Micro-separation for PCD 75 degree

Figure 5c and 5d illustrate the 1st Principal stress developed in the acetubular cup for the material PCD for 45-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum 1st Principal stress was developed for the 45 degree at 2 mm micro-separation and it is 540.33 MPa. The minimum 1st Principal stress was developed for the 45 degree at 0 mm micro-separation and it is 75.001 MPa. Figure 5e&f illustrate the 1st principal stress developed in the acetubular cup for the material PCD for 55-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum 1st principal stress was developed for the 55 degree at 2.5 mm micro-separation and it is 308.43 MPa. The minimum 1st principal stress was developed for the 55 degree at 0 mm micro-separation and it is 69.08 MPa. Figure 5g & h illustrate the 1st Principal stress developed in the acetubular cup for the material PCD for 65-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum 1st principal stress was developed for the 65 degree at 0.5 mm micro-separation and it is 260.38 MPa. The minimum 1st Principal stress was developed for the 65 degree at 0 mm micro-separation and it is 74.04 MPa. Figure 5i & j illustrate the 1st Principal stress developed in the acetubular cup for the material PCD for 75-degree inclination angle and various micro-separation such as 0, 0.5, 1, 1.5, 2, and 2.5 mm. The maximum 1st principal stress was developed for the 75 degree at 0.5 mm micro-separation and it is 214.75 MPa. The minimum 1st Principal stress was developed for the 75 degree at 0 mm micro-separation and it is 66.31 MPa.

4. Discussion

Overall contact pressure was found to be effectively reduced when compared with other metallic biomaterials like CoCr which was analysed for contact mechanics for different cup rim parameter design [24]. Another interesting fact is that the contact pressure was effectively contained for PCD material when compared with risky gait activities even for high head lateral displacements irrespective of cup inclinations. The present study also focused on load values ranging from 2700 to 7000 N, while most of the previous studies limited to only fixed load[24], wherein it would be difficult to analyse contact mechanics behaviour. The present approach could be extended further by varying different parameters of hip design which includes radial clearance, head diameter and cup thickness reported in previous studies[25, 26]. This could further improve concept of elevated acetabular cup design approach for effective reduction of contact mechanics.

5.Conclusion

The analysis showed that 0 mm micro-separation condition produced the most favorable results, with minimal edge loading and lower contact stresses, first Principal stress, compressive stress and von Mises stress compared with other micro-separation 0.5, 1, 1.5, 2, and 2.5 mm micro-separation. At 0 mm micro-separation ensures the stable articulation between the femoral head and cup and reduces the wear, preventing rim loading, and enhancing the overall performance and longevity of the implant. It was observed that a 75° elevated inclination angle of the acetabular cup provided better bio-mechanical results. This configuration resulted in more uniform stress distribution, reduced edge loading, and improved joint stability compared to lower inclination angles such as 35°, 45°, 55°, and 65°. The elevated angle enhanced the contact conformity and minimize the wear and extending implant life.

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