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# Relationship between deformation and running-in wear on hard-on-hard bearings from metal, ceramic, and diamond materials for total hip prosthesis

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ABSTRACT

Since polyethylene wear particles reduce the lifetime of the total hip prosthesis in hard-on-soft bearing couples, hard-on-hard applications are more promising. Running-in wear evaluation can be the basis for determining the material selection for the hard-on-hard bearing couple. In addition, each material for hard-on-hard has a different magnitude of deformation during loading conditions. The current work gains an in-depth understanding relationship between deformation and running-in wear on three different hard materials: metal, ceramic, and diamond for use in hard-on-hard bearing couples. Computational study with a two-dimensional finite element-based model has been chosen to obtain the deformation of hard-on-hard bearing couples under simulated walking conditions and then compared with the running-in linear and volumetric wear to understand the relationship. The results show that with less deformation the hard-on-hard bearings exhibit lower running-in linear and volumetric wear.

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## 1.0 INTRODUCTION

It is widely recognized that the total hip prosthesis is one of the most successful applications of biomaterials in the medical industry (Australian Orthopaedic Association National Joint Replacement Registry, 2020; Keele University, 2014; London Health Sciences Centre, 2013). In general, the materials used as bearing couple consist of hard material and soft material. The hard material is ceramic and metal, while the soft material is polyethylene. With two different types of materials, the bearing couple is made with a combination of hard-on-hard (Baleani et al., 2017) and hard-on-soft (Triantafyllou et al., 2021) materials. Hard-on-soft bearing, such as metal-on-polyethylene (Su et al., 2021) and ceramic-on-polyethylene (Posada et al., 2015) have been used extensively in total human hip joint replacement. Unfortunately, the wear particles of polyethylene reduce the use time of total hip prosthesis. Therefore, hard-on-hard bearing, such as metal-on-metal (Apostu et al., 2022) and ceramic-on-ceramic (Triantafyllou et al., 2021) were then chosen to improve the performance of hip implants in the drawback's anticipation of polyethylene.

However, until now there are still crucial problems in hard-on-hard bearing, such as the occurrence of osteolysis due to metal ions from metal wear particles in metal-on-metal bearings (Pozzuoli et al., 2020) and failure due to fracture in ceramic-on-ceramic bearings due to unexpected activities (Burger and Kiefer, 2021). To solve the existing problems, Polycrystalline diamond (PCD) has been proposed as a potential hard-on-hard bearing material due to its outstanding mechanical properties, such as high hardness, low friction, toughness, and superior biocompatibility (Sinusia Lozano et al., 2022; Ramírez et al., 2022; Li et al., 2021). This material is produced from small diamond grains in a high-temperature and high-pressure sintering environment (Guignard et al., 2022a, 2022b; Omole et al., 2022).

Many experimental tests have been carried out to investigate the bearing of the hip joint prosthesis, but the high cost and short time become burdensome (Rontescu et al., 2022; Solórzano-Requejo et al., 2022). To overcome these obstacles, a computational simulation-based study using the finite element method is an effective solution in providing an understanding of the bearing's implant performance. The use of a three-dimensional finite element model has been used by Torre et al. (De la Torre et al., 2021) to analyze the risk of wear from cement and uncemented polyethylene liners of total hip prosthesis. Unfortunately, the use of three-dimension models requires sufficient computational capabilities with a longer estimation time. Simplification of the finite element model into two-dimension as done by Ammarullah et al. (Ammarullah et al., 2022b) to study the effect of ceramic materials on the Tresca stress of bearing couple of total hip prosthesis can be a solution to the problems faced by the adoption of a three-dimension model. The change in finite element model on bearing of total hip prosthesis from three dimensions to two dimensions refers to the computational simulation results by Cilingir et al. (Cilingir et al., 2007), which explains the difference in results between both of them does not have a significant difference.

Wear is one of the reasons causes the failure of the total hip prosthesis which is dangerous for the user (Dammer et al., 2022). Material selection for the bearing of total hip prosthesis is crucial to reducing wear, especially during the running-in phase (shown in Figure 1), which is the initial time when the wear rate on the bearing couple is very high (Lee et al., 2019). The investigation of wear on total hip prosthesis with different bearing materials has been approached with computational simulations previously performed by Uddin and Zhang (Uddin and Zhang, 2013), Milone et al. (Milone et al., 2022), and Jangid et al (Jangid et al., 2019). Previous studies used contact pressure to obtain wear based on the Archard wear equation. This is in line with the statement of Jamari et al. (Jamari et al., 2022) that the greater the contact pressure would impact to greater the intensity of wear. Unfortunately, it does not appropriate when comparing contact pressure values with different hard materials, such as metal, ceramics, and diamonds because different materials combinations have different wear coefficients and also contribute to wear evolution.

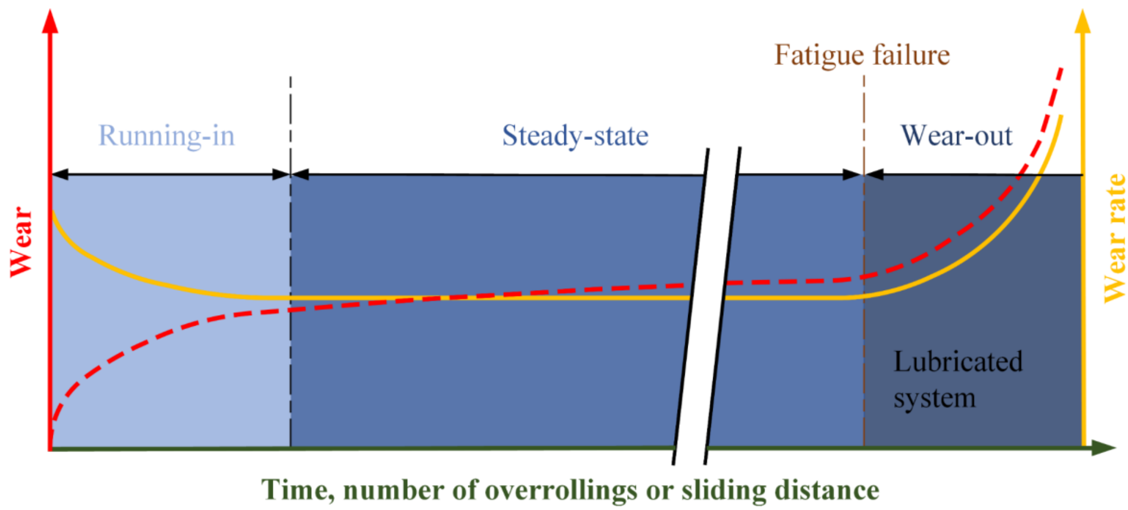


Figure 1: Schematic representation of wear behavior.

In addition to contact pressure and wear, aspects of deformation have also been carried out to assess the bearing performance of the total hip prosthesis. Deformation studies with computational simulation have also previously been carried out as carried out by Vogel et al. (Vogel et al., 2020), Affatato et al. (Affatato et al., 2017), and Jamari et al. (Jamari et al., 2014). Hard-on-hard bearings have different deformations according to the mechanical characteristics of the hard material used. It is widely recognized that the greater deformation on the bearing of total hip prosthesis impacts the greater risk of implant failure. Unfortunately, there are no studies that describe in detail the relationship between deformation and running-in wear in the investigation of hard-on-hard bearings of total hip prosthesis.

The present paper aims to find the relationship between deformation and running-in wear from hard-on-hard bearings with three different hard materials, namely metal-on-metal, ceramic-on-ceramic, and diamond-on-diamond. A computational simulation using the two-dimension finite element method has been chosen to study the deformation of bearing couple under normal walking conditions. Then, the relationship between deformation and running-in wear is carried out by comparing the deformation simulation results obtained with the linear wear and volumetric wear values from previous studies conducted by Uddin and Zhang (Uddin and Zhang, 2013).

## 2.0 MATERIALS AND METHODS

### 2.1 Size and Materials of Hard-On-Hard Bearing Couple

Bearing couple geometry selected for femoral head and acetabular cup component in this study is adopted from previous research by Jamari et al. (Jamari et al., 2021), where femoral head diameter is 28 mm, radial clearance is 0.05 mm, and acetabular cup thickness is 5 mm. This geometric parameter was commonly used for a bearing couple of total hip implants, especially for Indonesian and mostly Asians. The evaluated materials for hard-on-hard bearing couples in this computational simulation are Cobalt Chromium Molybdenum (CoCrMo), Aluminum Oxide ($Al_2O_3$), and PCD assuming the material is homogeneous, isotropic, and linear elastic. Properties of materials are Young's modulus and Poisson's ratio for CoCrMo is 210 GPA and 0.3 (Ammarullah et al., 2021), $Al_2O_3$ is 375 GPa and 0.3 (Ammarullah et al., 2022b), and PCD is 900 GPa and 0.1 (Chen et al., 2006), respectively. The effect of lubrication and surface roughness on the bearing couple is represented by considering the friction on the bearing interface given by entering the friction coefficient value in the computational model. The friction coefficient values were adopted from previous studies: 0.2 for CoCrMo-on-CoCrMo (Ammarullah et al., 2022a), 0.1 for $Al_2O_3$-on-$Al_2O_3$ (Ammarullah et al., 2022b), and 0.1 for PCD-on-PCD (Feng and Field, 1992).

### 2.2 Finite Element Model of Hard-On-Hard Bearing Couple

A hard-on-hard bearing couple is made by considering two main components, namely the femoral head and acetabular cup. The definition of contact at the bearing interface, master surface and slave surface, is defined as contact surface at the femoral head and acetabular cup, respectively. A computational study with a two-dimensional finite element model was chosen for reasons of efficiency without significantly reducing results accuracy, where we used a ball-in-socket asymmetry model to form a quarter circle (Jamari et al., 2022). Additionally, the contact process disregards the possibility of micro-separation due to the femoral head being concentric to the acetabular cup.

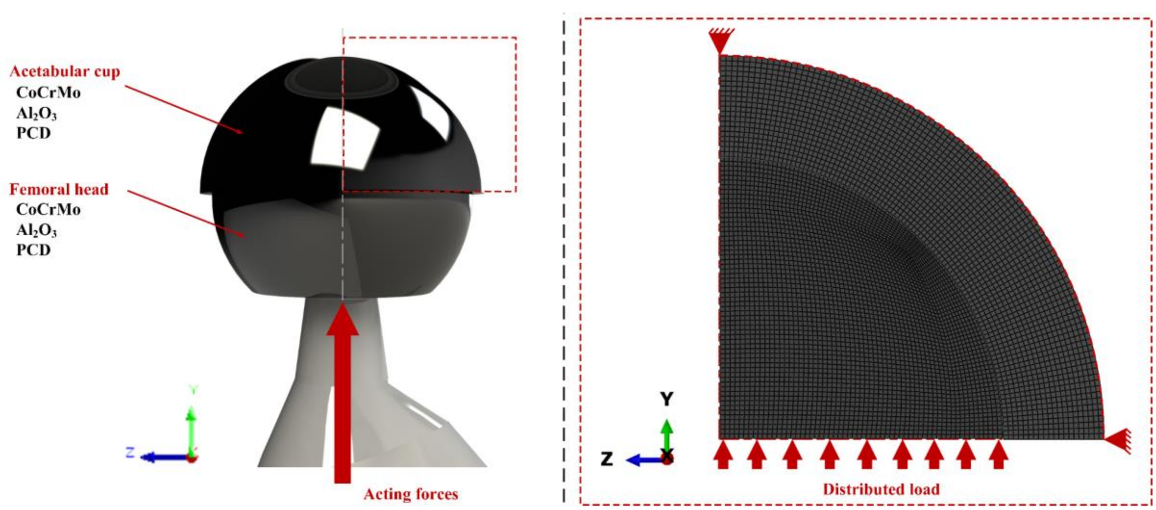


Figure 2: Two-dimension finite element model of hard-on-hard bearing couple.

The number of elements was chosen by conducting a convergence study using the H-refinement method on both components, femoral head and acetabular cup. A total of 5500 CAX4 elements were used to model the hard-on-hard bearing couple, where 2000 CAX4 elements were for the acetabular cup component and the rest for the femoral head component. Steady-state evaluation of deformation was carried out using ABAQUS/CAE 6.14-1. The effect of lubrication during contact is neglected by considering only dry contact that uses the coefficient of friction as a representative of the lubrication effect. The boundary conditions in the finite element model are given by making the outer surface of the acetabular cup a fixed constraint and applying a concentrated load to the bottom of the acetabular cup as described in Figure 2.

### 2.3 Loading Under Normal Walking

The computational simulation of a hard-on-hard bearing couple is carried out by simulated normal walking conditions. This is based on the most common daily activity for implant users who have undergone hip joint replacement surgery is normal walking (Uddin and Zhang, 2013). Figure 3 describes the normal walking conditions used in this study from Bergmann et al. (Bergmann et al., 2001) obtained from the measurements of four different patients with an average body weight of 85.3 kg and body height of 171 cm. To simplify the computational process, normal walking condition is divided into 32 phases as done by Jamari et al. (Jamari et al., 2021). One normal walking cycle consists of two main phases, namely the 'stance phase' ($1^{st}$ - $19^{th}$ phase, 60% starting process of normal walking cycle) and 'swing phase' ($20^{th}$-$32^{nd}$ phase, 40% ending process of normal walking cycle). In the present study, only gait loading is considered in terms of the resultant force by ignoring the range of motion as done by Jamari et al. (J Jamari et al., 2022). The magnitude of applied force changes with the phase in the normal walking cycle, where the highest value is found in the $7^{th}$ phase, and the lowest in the $30^{th}$ phase.

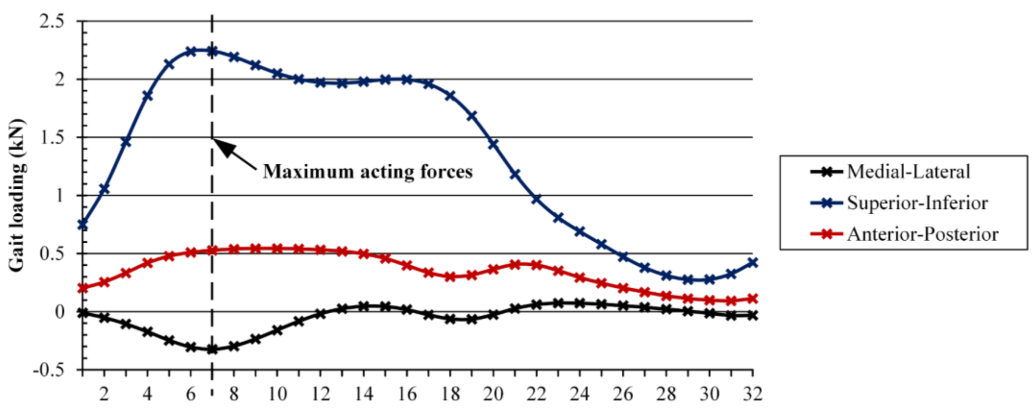


Figure 3: Acting forces during normal walking (Ammarullah et al., 2021).

### 2.4 Running-in Linear and Volumetric Wear Comparison

Deformation of the CoCrMo-on-CoCrMo, $Al_2O_3$-on-$Al_2O_3$, and PCD-on-PCD bearings in the current study will be compared with running-in linear and volumetric wear from previous studies conducted by Uddin and Zhang (Uddin and Zhang, 2013) to understand their relationship . The comparison of linear and volumetric wear is taken during the running-in phase, which is the wear that occurs in the couple bearings during $1 \times 10^6$ walking cycles. The study was adopted for comparison with the deformation of the current study because it has identical conditions, both in terms of geometry, material properties, and loading.

## 3.0 RESULTS AND DISCUSSION

The maximum deformation of hard-on-hard bearing couples under simulated walking conditions is shown in Figure 4. Also, a comparison between the highest, average, and lowest maximum deformation on the hard-on-hard bearing is presented in Figure 5. In the 7$^{th}$ phase, the largest deformation occurred in the three types of hard-on-hard bearings studied, while the lowest was found in the 30$^{th}$ phase. This is because the 7$^{th}$ and 30$^{th}$ phases are the highest and lowest acting forces under the conditions of the applied load. Deformation in hard-on-hard bearings continues to change in one loading cycle due to changing acting forces over time.

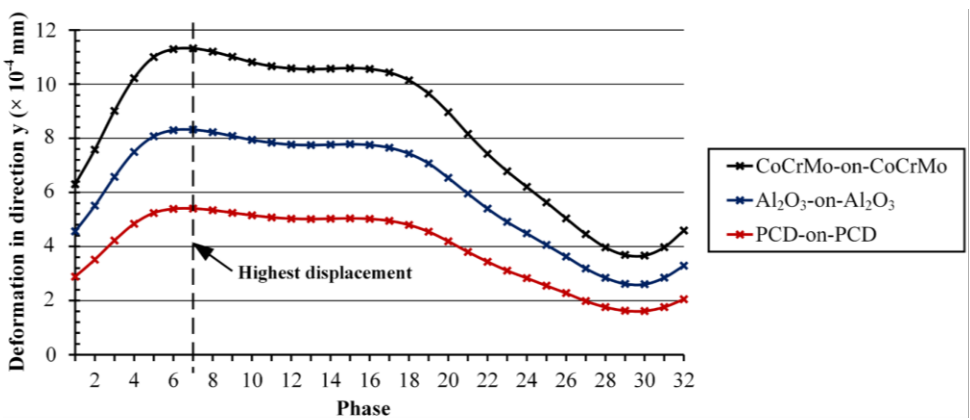


Figure 4: Maximum deformation for hard-on-hard bearing couple in full cycle.

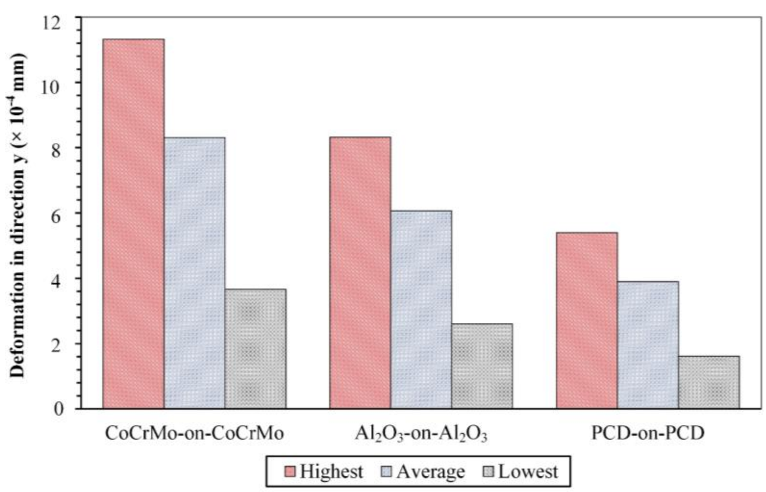


Figure 5: Highest, average, and lowest maximum deformation of a hard-on-hard bearing couple under walking condition.

Deformation distributions for hard-on-hard bearing couples are shown in Figure 6 using U2 terminology in ABAQUS/CAE 6.14-1 (Dassault Systèmes, 2016). Since the gait cycle does not consider the range of motion, the deformation distribution is always in the center of the acetabular cup. For realistic loading, the resultant force and range of motion need to be considered because normal walking conditions over time give the resultant force in different directions. When a repeated large deformation occurs in bearing couples, it will disrupt the fixation system and lead to instability failing the total hip prosthesis (Terrier et al., 2017). In addition, it can also cause plastic deformation, where the bearing material loses its elastic properties and cannot return to its original shape (Jamari and Schipper, 2008).

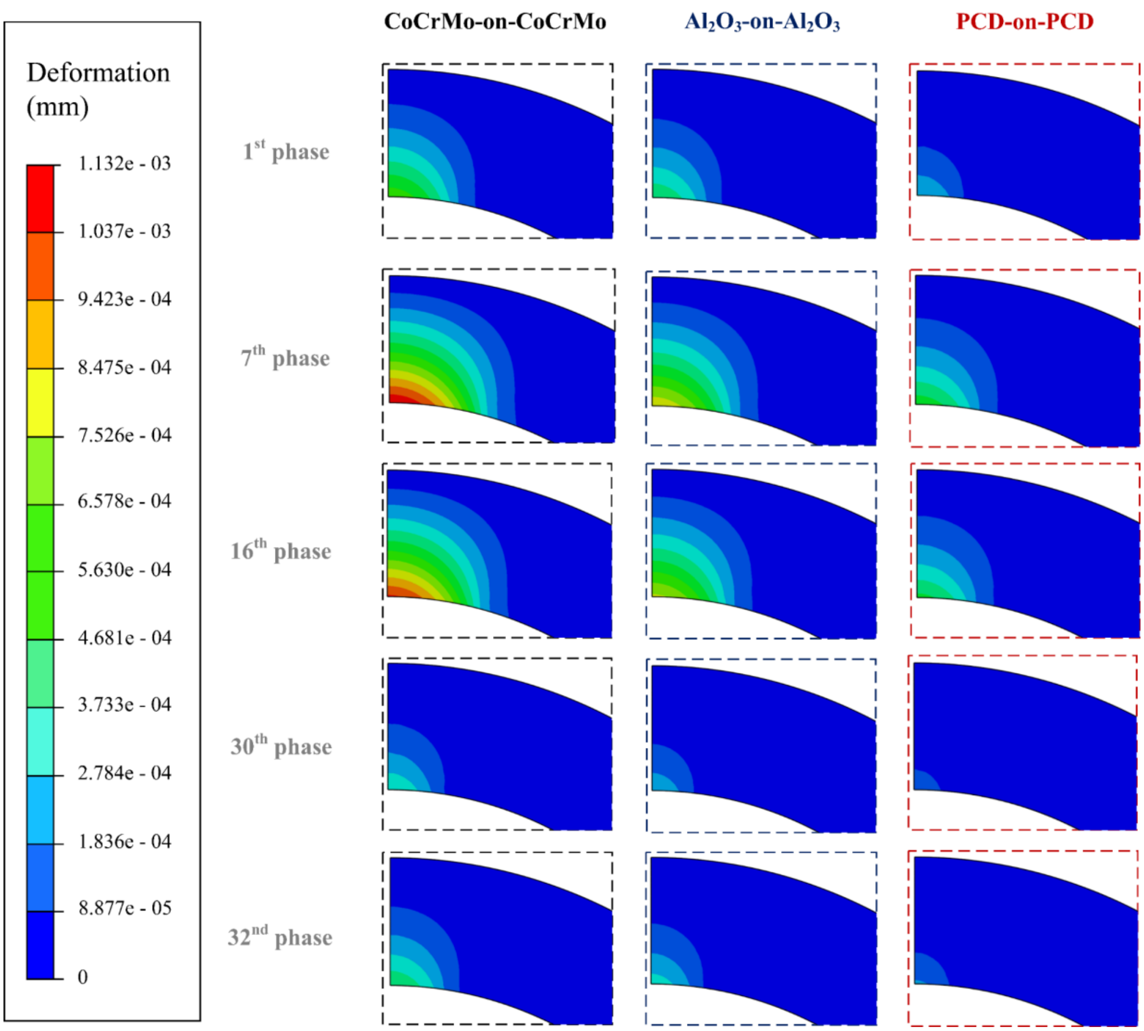


Figure 6: Deformation distribution on the acetabular cup for hard-on-hard bearing couple at a selected phase.

Figure 7 and Figure 8 present the relationship between deformation and contact radius of hard-on-hard bearing couples at maximum acting forces and selected phases, respectively. In the selected phase with the same material, the deformation and contact radius will be even greater with the magnitude of the resultant force applied. The Young's modulus property of the material for hard-on-hard bearings greatly affects the deformation, where the higher the value of Young's modulus, the harder the material will be (Rodaev et al., 2021). PCD has an extraordinary Young's modulus property, which is 900 MPa. Its Young modulus is extremely high compared to CoCrMo and $Al_2O_3$, which are only 210 MPa and 375 MPa, respectively. Therefore, it is clear that PCD-on-PCD has the best ability to reduce deformation compared to CoCrMo-on-CoCrMo and $Al_2O_3$-on-$Al_2O_3$.

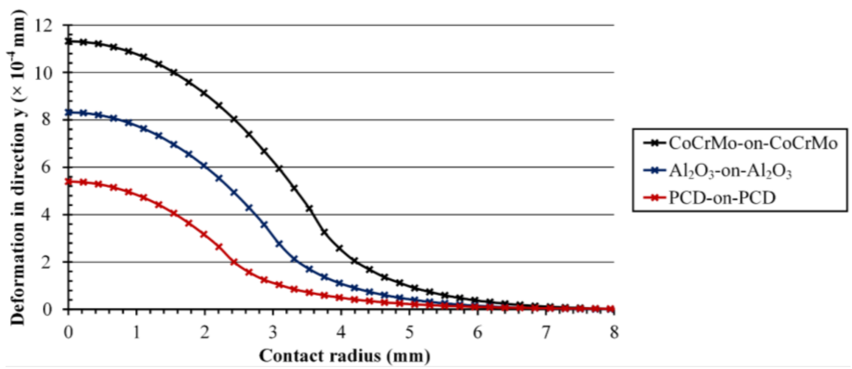


Figure 7: Deformation profile as a function of contact radius for different hard-on-hard bearing couple at maximum acting forces.

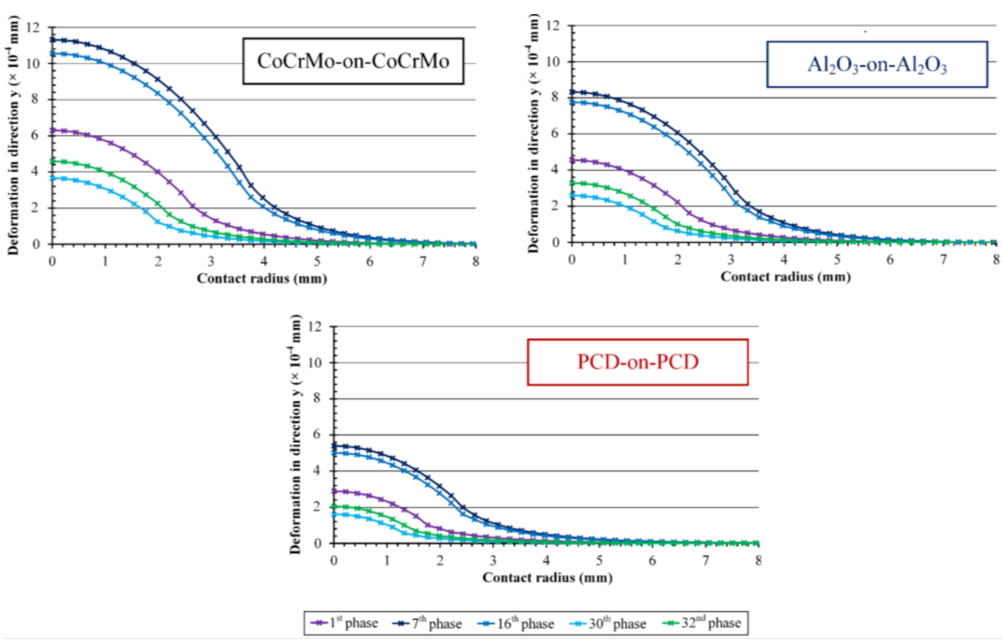


Figure 8: Deformation profile as a function of contact radius for different hard-on-hard bearing couple at maximum acting forces.

Table 1 describes the maximum deformation in the present study compared to running-in linear and volumetric wear for different hard-on-hard bearing couples adopted from Uddin and Zhang (Uddin and Zhang, 2013). Furthermore, the relationship between them is shown in Figure 9. CoCrMo-on-CoCrMo has the largest maximum deformation in this study of 0.00113 mm, compared to $Al_2O_3$-on-$Al_2O_3$ of 0.000832 mm, and the smallest is PCD-on-PCD of 0.00054 mm. Maximum deformation has a directly proportional relationship with linear and volumetric running-in wear, where PCD-on-PCD bearings which are the bearings with the smallest maximum deformation have the smallest linear and volumetric running-in wear of 0.0635 m and 0.00292 $mm^3$, respectively compared to CoCrMo-on-CoCrMo and $Al_2O_3$-on-$Al_2O_3$.

Table 1: Maximum deformation, running-in linear wear, and running-in volumetric wear for different hard-on-hard bearing couple.

| **Bearing material** | **Maximum Deformation (present study)** | **Running-in linear wear (Uddin and Zhang, 2013)** | **Running-in volumetric wear (Uddin and Zhang, 2013)** |
|---|---|---|---|
| CoCrMo-on-CoCrMo | 0.00113 mm | 2.5 μm | 0.42 $mm^3$ |
| Al2O3-on-Al2O3 | 0.000832 mm | 1.317 μm | 0.17275 $mm^3$ |
| PCD-on-PCD | 0.00054 mm | 0.0635 μm | 0.00292 $mm^3$ |

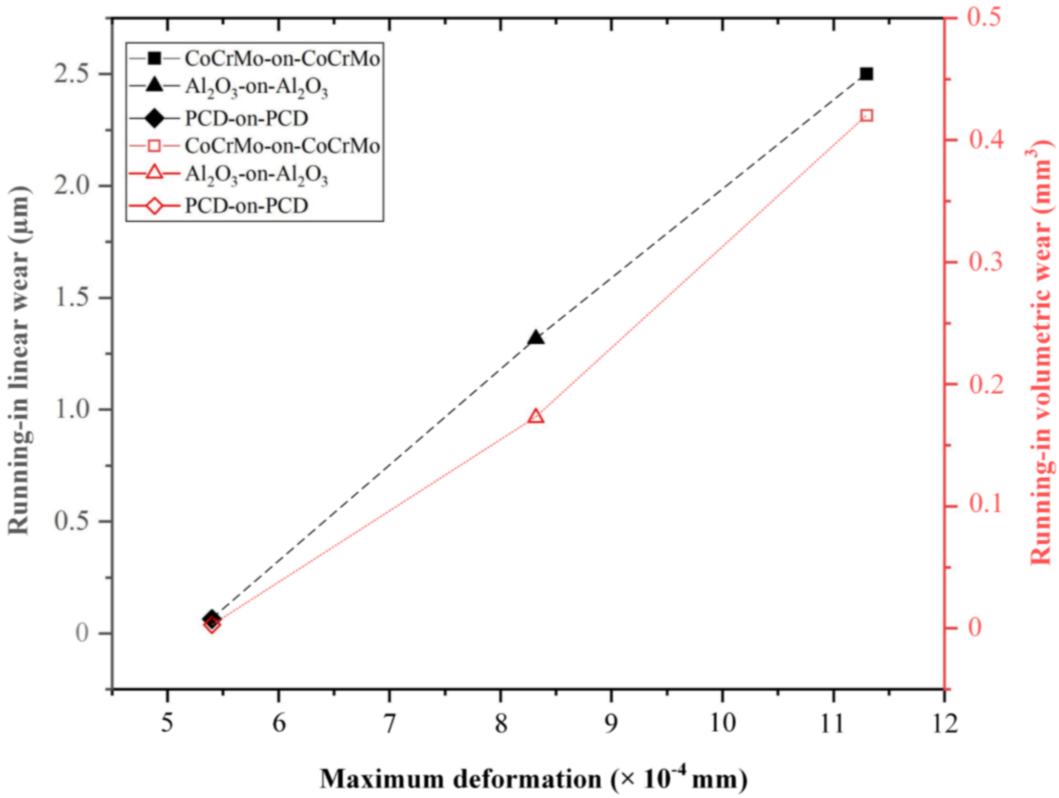


Figure 9: Relationship between deformation and running-in linear and volumetric wear.

Several important points need to be conveyed regarding the limitations of the current research. First, the loading with normal walking conditions only adopts the resultant force, but not with the range of motion which makes the force application only has one direction. It does not reflect the realistic conditions when patients using implants carry out normal walking activities (Luo et al., 2019). Furthermore, the use of a constant friction coefficient during the analysis process. The value of the coefficient of friction always changes over time according to the lubrication conditions, surface roughness, and wear on the bearing surfaces (Kandeva et al., 2022). Furthermore, to speed up the computation time required, the modeling only uses two-dimensional finite element models that are less close to the real conditions compared to the three-dimensional model (Jamari et al., 2022). And finally, bearing couples only consider the femoral head and acetabular cup components. Whereas considering other components, such as the pelvic bone and fixation system, can provide a modeling condition more realistic (Abdullah and Todo, 2021). The current limitations can certainly affect the results obtained, therefore these shortcomings need to be addressed in future research to find out.

## CONCLUSIONS

In this work, three different materials, including metal, ceramic, and diamond for hard-on-hard bearing couples have been evaluated on their deformation using a two-dimensional finite element model. Under normal walking conditions, the highest deformation was found in the $7^{th}$ phase with the same pattern for all simulated hard-on-hard bearing couples. PCD-on-PCD is a potential bearing considering its extraordinary ability to reduce deformation compared to other hard-on-hard bearings. Linear and volumetric running-in wear on PCD-on-PCD bearings were also found to be the lowest compared to CoCrMo-on-CoCrMo and $Al_2O_3$-on-$Al_2O_3$. It is showing the directly proportional relationship between deformation and running-in wear, both linear wear and volumetric wear to be less along with less deformation in hard-on-hard bearings.

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