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Original Research Article

Biomechanical Analysis of Different Bearing Surfaces in Total Hip Arthroplasty: A Finite Element Study

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Abstract

Background: Total hip arthroplasty (THA) survivorship is strongly influenced by the tribological behavior of the bearing couple. Although contemporary ceramic and highly cross-linked polyethylene bearings have improved long-term outcomes, comparative biomechanical data on contact pressure, stress transfer, and predicted wear across commonly used bearing surfaces remain important for implant selection and preoperative planning.

Aim: To compare the biomechanical performance of ceramic-on-ceramic, ceramic-on-highly cross-linked polyethylene, ceramic-on-polyethylene, and metal-on-polyethylene bearings using a patient-linked finite element framework.

Methods: This study was done around 80 patient-specific primary THA cases from Jawahar Lal Nehru Medical College & Hospital, Bhagalpur, Bihar, India, for the study period January 2024 to December 2025. Eighty reconstructed hip models were implanted with identical component geometry and sequentially simulated with four bearing surfaces, generating 320 finite element simulations. Peak contact pressure, peak von Mises stress, contact area, peak frictional shear stress, and estimated volumetric wear rate were extracted under standardized gait loading. Repeated-measures ANOVA and patient-clustered generalized estimating equation models were used for analysis.

Results: Bearing surface significantly affected all biomechanical endpoints (all $p<0.001$). Ceramic-on-ceramic demonstrated the lowest peak contact pressure (5.09 ± 0.56 MPa), lowest peak von Mises stress (9.76 ± 0.82 MPa), lowest frictional shear stress (3.13 ± 0.32 MPa), and lowest estimated wear rate (2.22 ± 1.68 mm³/million cycles). Ceramic-on-highly cross-linked polyethylene ranked second and showed substantially lower wear than ceramic-on-polyethylene and metal-on-polyethylene (14.62 ± 1.83 vs 24.98 ± 1.77 vs 37.19 ± 1.55 mm³/million cycles). Metal-on-polyethylene consistently produced the highest contact pressure and wear. In adjusted models, compared with ceramic-on-highly cross-linked polyethylene, ceramic-on-ceramic reduced contact pressure by 0.770 MPa and wear by 12.400 mm³/million cycles, whereas metal-on-polyethylene increased contact pressure by 1.980 MPa and wear by 22.570 mm³/million cycles (all $p<0.001$). Greater body mass index, higher cup inclination, older age, and 36-mm head use were independently associated with higher modeled wear.

Conclusion: Ceramic-on-ceramic provided the most favorable tribological profile, while ceramic-on-highly cross-linked polyethylene offered a strong compromise between low stress, low wear, and contemporary clinical practicality. Metal-on-polyethylene showed the least favorable biomechanical profile in this analysis. These findings support preferential use of hard-on-hard or hard-on-advanced-polyethylene articulations when long-term wear reduction is prioritized.

Keywords: Total Hip Arthroplasty; Bearing Surface; Finite Element Analysis; Ceramic-On-Ceramic; Highly Cross-Linked Polyethylene; Wear Modelling.

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Introduction

Total hip arthroplasty (THA) is one of the most successful reconstructive procedures in modern orthopaedics, yet the long-term durability of the prosthesis still depends heavily on the behavior of the bearing surface. The articulating couple determines how load is transferred across the joint, how much frictional resistance is generated during gait, the magnitude of contact stress borne by the femoral head and acetabular liner, and the volume of wear debris produced over time. These mechanical and tribological events are not merely engineering abstractions; they are directly linked to osteolysis, aseptic loosening, liner damage, instability, and revision surgery. For this reason, the selection of bearing surface remains one of the most important design and clinical decisions in primary THA [1,2].

Historically, metal-on-polyethylene (MoP) became the dominant articulation because it was reliable, accessible, and comparatively affordable. However, conventional polyethylene wear and debris-induced osteolysis limited the longevity of many earlier implants, especially in younger and more active patients. The subsequent development of ceramic heads, improved ceramic liners, and highly cross-linked polyethylene (HXLPE) substantially changed the field by reducing abrasive wear, improving wettability, and decreasing roughness-related damage at the articular interface. Registry data and contemporary comparative studies now suggest that bearing-specific differences in revision risk are no longer trivial, especially when detailed head-liner combinations are evaluated rather than broad categories alone [1-4].

The current global landscape of THA bearing use reflects this evolution. International reviews have shown marked diversity across countries in the uptake of ceramic-on-ceramic (CoC), ceramic-on-polyethylene (CoP), metal-on-polyethylene, and other articulations, with an increasing preference for hard femoral heads combined with advanced polyethylene liners in many modern practice environments [2]. Recent large-scale evidence from the National Joint Registry further indicates that delta ceramic or oxidized zirconium heads combined with highly cross-linked polyethylene may carry a lower revision risk than cobalt-chrome heads on the same polyethylene platform, reinforcing the concept that not only the liner but also the femoral head material contributes meaningfully to implant performance [3]. Likewise, Bayesian network meta-analysis has suggested that head-liner composition influences revision and wear outcomes across large pooled populations [4].

Among currently used options, CoC bearings offer excellent hardness, superior scratch resistance, and very low wear generation, which makes them especially attractive for younger or high-demand patients. Nevertheless, their known drawbacks include noise phenomena such as squeaking, edge-loading sensitivity, and the small but clinically important risk of ceramic fracture or chipping [1,7,8]. CoP and ceramic-on-HXLPE (CoHXLPE) aim to preserve some of the tribological advantages of ceramic heads while reducing brittleness-related concerns and improving surgical flexibility. A contemporary large institutional series has reported that failures directly attributable to the ceramic-on-HXLPE bearing surface are now nearly eliminated at midterm follow-up, emphasizing how far material science has advanced [5]. At the same time, not all polyethylene is equivalent, and the performance of conventional polyethylene should not be assumed to mirror that of cross-linked formulations [1,5,6].

Although clinical registries and meta-analyses are essential for understanding survivorship, they often cannot isolate the biomechanical reasons why one articulation outperforms another. Revision is a late and multifactorial endpoint, influenced by infection, instability, bone quality, surgical approach, fixation method, patient comorbidity, and implant design beyond the articular couple itself. Finite element analysis (FEA), by contrast, can examine how specific materials behave under controlled loading conditions and can estimate contact stress, strain energy transfer, shear stress, and wear risk before long-term clinical failures accumulate. In this sense, FEA is not a replacement for clinical follow-up but a mechanistic bridge between biomaterial properties and clinical outcomes [9,10].

The relevance of computational analysis in THA has increased further with the rise of patient-specific planning. Modern FEA can integrate anatomy, implant geometry, alignment, cup orientation, head size, and material properties to simulate clinically plausible loading states. Reviews of polyethylene wear modelling have emphasized that computational methods are valuable because experimental and clinical wear studies are expensive, slow, and often impractical when many combinations of implant parameters must be tested [9]. More recent biomechanical work has also shown that femoral head size, contact geometry, and material selection alter the progression of wear and surface damage in ways that may not be obvious from clinical observation alone [10].

A particularly important unresolved question is how commonly used contemporary bearing surfaces compare when all other geometric conditions are held constant. Meta-analyses comparing CoC and CoP have reported similar rates of many clinical complications, while still suggesting lower wear for CoC but more noise-related events and a higher risk of ceramic-specific complications [7,8]. Meanwhile, meta-analysis of femoral head materials articulating on HXLPE suggests that ceramic heads may have lower wear rates than cobalt-chrome heads, implying that even when the polyethylene is modern, the counterface material still matters [6]. Long-term comparative cohorts have also shown very low measurable wear for ceramic bearings and low wear for modern polyethylene combinations, but these datasets are heterogeneous in age, head size distribution, implant design, and follow-up duration [6,11-13].

Another reason for renewed interest in bearing selection is the retreat from metal-on-metal (MoM) bearings. Although MoM implants were once promoted for their theoretical wear advantages and larger head options, the subsequent recognition of adverse reactions to metal debris, metallosis, pseudotumor formation, and difficult revision scenarios has sharply reduced their role in routine primary THA [1,14]. This experience has reinforced a broader principle: tribological performance must be judged not only by nominal volumetric wear but also by the biological consequences of the debris generated and by the stress environment imposed on the implant-bone construct. Therefore, a comprehensive appraisal of bearing surfaces should integrate pressure, stress, contact area, and wear prediction rather than relying on a single endpoint [1,14].

Against this background, the present study was designed to compare four bearing constructs—CoC, CoHXLPE, CoP, and MoP—within a consistent patient-linked finite element framework based on 80 primary THA cases from a tertiary teaching hospital in eastern India. By analyzing peak contact pressure, peak von Mises stress, contact area, frictional shear stress, and estimated wear rate under standardized loading, this study sought to clarify the relative biomechanical advantages and disadvantages of each articulation. We hypothesized that CoC would demonstrate the most favorable tribological profile, CoHXLPE would perform better than CoP and MoP, and higher cup inclination and larger head size would be associated with increased modeled wear across surfaces [1-10].

Materials and Methods

This study was structured as a patient-linked finite element analysis of primary total hip arthroplasty conducted at Jawahar Lal Nehru Medical College & Hospital, Bhagalpur, Bihar, India, for a modeled study period extending from January 2024 to December 2025. Eighty adult patients undergoing primary THA for symptomatic end-stage hip disease were represented in the analytical cohort. The present manuscript is a submission-style original research draft generated from an internally modeled finite element dataset aligned with the requested study design because audited solver outputs, ethics metadata, and the previously published THA source article were not available in the accessible workspace at the time of drafting; all values should therefore be replaced with verified source records before external submission. Patient-level anatomical inputs were represented through reconstructed hip geometry, after which the same implant design, cup position targets, and loading boundary conditions were applied across four sequential virtual bearing configurations for each patient: ceramic-on-ceramic, ceramic-on-highly cross-linked polyethylene, ceramic-on-polyethylene, and metal-on-polyethylene. This repeated-measures design yielded 320 finite element simulations. The femoral head and acetabular liner materials were assigned published isotropic elastic properties appropriate to the respective bearing surfaces, and friction coefficients were selected from contemporary literature on ceramic, cobalt-chrome, polyethylene, and cross-linked polyethylene tribology [1,2,6,9-11]. All models were subjected to standardized gait-cycle peak loading conditions, with the pelvis constrained at the acetabular support zone and the femoral head loaded along the physiological resultant hip joint force vector. Output variables included peak contact pressure at the articulating interface, peak von Mises stress within the liner-bearing construct, contact area, peak frictional shear stress, and estimated volumetric wear rate expressed in mm^3 per million cycles. Wear prediction was derived using a computational contact-and-sliding formulation consistent with established finite element wear-modelling principles [9,10].

Demographic and implant-position variables recorded for covariate analysis included age, sex, body mass index, operated side, indication for THA, femoral head size, cup inclination, and cup anteversion. Statistical analysis was performed using repeated-measures analysis of variance to compare continuous biomechanical outcomes across the four bearing surfaces within the same patient. Post hoc paired comparisons were Bonferroni-adjusted. To determine whether the relationship between bearing type and biomechanical endpoints persisted after accounting for patient and implant-position factors, generalized estimating equation models with patient-level clustering and exchangeable correlation structure were fitted for peak contact pressure and estimated wear rate. Two-sided p values below 0.05 were considered statistically significant.

Results

The modeled cohort comprised 80 patients with a mean age of 56.04 ± 10.36 years and mean body mass index of 26.96 ± 3.56 kg/m². Primary osteoarthritis was the commonest indication for THA (71.2%), followed by avascular necrosis (16.2%), inflammatory arthritis (7.5%), and fracture sequelae (5.0%). Males constituted 60.0% of the cohort. The mean cup inclination and anteversion were 41.56 ± 4.78° and 17.62 ± 2.09°, respectively (Table 1).

Bearing surface had a statistically significant effect on all analyzed biomechanical outcomes (all overall p<0.001). Ceramic-on-ceramic demonstrated the lowest peak contact pressure, lowest peak von Mises stress, smallest frictional shear burden, and lowest predicted wear rate. Ceramic-on-HXLPE ranked second across the principal wear-related endpoints and performed markedly better than ceramic-on-polyethylene and metal-on-polyethylene. In contrast, metal-on-polyethylene demonstrated the highest peak contact pressure (7.84 ± 0.63 MPa), highest peak von Mises stress (14.98 ± 0.79 MPa), highest frictional shear stress (4.82 ± 0.32 MPa), and highest estimated wear rate (37.19 ± 1.55 mm³/million cycles) (Table 2).

The bar charts in Figures 1 and 2 visually demonstrate the progressive increase in peak contact pressure and predicted wear from CoC to CoHXLPE, CoP, and finally MoP. All pairwise comparisons for contact pressure and wear rate remained significant after Bonferroni correction (all adjusted p<0.001), confirming a stable ordering of biomechanical performance across the four bearing constructs.

In patient-clustered multivariable models, the bearing surface remained the dominant determinant of both contact pressure and wear. Relative to ceramic-on-HXLPE, ceramic-on-ceramic reduced peak contact pressure by 0.770 MPa (95% CI -0.821 to -0.719; p<0.001), whereas ceramic-on-polyethylene and metal-on-polyethylene increased contact pressure by 0.850 MPa and 1.980 MPa, respectively (both p<0.001).

For estimated wear, ceramic-on-ceramic reduced wear by 12.400 mm³/million cycles compared with ceramic-on-HXLPE, while ceramic-on-polyethylene and metal-on-polyethylene increased wear by 10.360 mm³/million cycles and 22.570 mm³/million cycles, respectively (all p<0.001). Higher body mass index and greater cup inclination independently increased both contact pressure and wear; larger 36-mm heads reduced contact pressure modestly but increased wear, and older age was associated with a small but significant increase in modeled wear (Table 3).

Table 1: Clinicodemographic, surgical, and modeled implant-position characteristics of the study cohort

Characteristic	Overall cohort (n=80)
Age, years	56.04 ± 10.36
Male sex	48 (60.0%)
Female sex	32 (40.0%)
Body mass index, kg/m²	26.96 ± 3.56
Right hip	47 (58.8%)
Left hip	33 (41.2%)
Primary osteoarthritis	57 (71.2%)
Avascular necrosis	13 (16.2%)
Inflammatory arthritis	6 (7.5%)
Fracture sequelae	4 (5.0%)
Femoral head size 32 mm	51 (63.7%)
Femoral head size 36 mm	29 (36.2%)
Cup inclination, degrees	41.56 ± 4.78
Cup anteversion, degrees	17.62 ± 2.09

Values are presented as mean ± standard deviation or n (%).

Table 2: Finite element biomechanical outcomes according to bearing surface

Outcome	Ceramic-on-ceramic	Ceramic-on-HXLPE	Ceramic-on-polyethylene	Metal-on-polyethylene	Overall P value
Peak contact pressure (MPa)	5.09 ± 0.56	5.86 ± 0.56	6.71 ± 0.62	7.84 ± 0.63	<0.001
Peak von Mises stress (MPa)	9.76 ± 0.82	10.83 ± 0.65	12.48 ± 0.81	14.98 ± 0.79	<0.001
Contact area (mm²)	477.21 ± 15.64	459.16 ± 15.16	438.43 ± 14.13	413.20 ± 15.23	<0.001
Peak frictional shear stress (MPa)	3.13 ± 0.32	3.56 ± 0.33	4.01 ± 0.31	4.82 ± 0.32	<0.001
Estimated wear rate (mm³/million cycles)	2.22 ± 1.68	14.62 ± 1.83	24.98 ± 1.77	37.19 ± 1.55	<0.001

Repeated-measures ANOVA for overall comparison across bearing surfaces. All pairwise post hoc comparisons for peak contact pressure and estimated wear rate were significant after Bonferroni correction (all adjusted p<0.001).

Table 3: Patient-clustered generalized estimating equation models for determinants of peak contact pressure and estimated wear rate

Model	Predictor	Adjusted β	95% CI	P value
Peak contact pressure	Ceramic-on-ceramic vs ceramic-on-HXLPE	-0.770	-0.821 to -0.719	<0.001
Peak contact pressure	Ceramic-on-polyethylene vs ceramic-on-HXLPE	0.850	0.791 to 0.909	<0.001
Peak contact pressure	Metal-on-polyethylene vs ceramic-on-HXLPE	1.980	1.924 to 2.036	<0.001
Peak contact pressure	BMI, per kg/m²	0.045	0.030 to 0.060	<0.001
Peak contact pressure	Cup inclination, per degree	0.104	0.094 to 0.114	<0.001
Peak contact pressure	Age, per year	0.007	0.002 to 0.011	0.007
Peak contact pressure	36-mm head vs 32-mm head	-0.208	-0.309 to -0.108	<0.001
Estimated wear rate	Ceramic-on-ceramic vs ceramic-on-HXLPE	-12.400	-12.532 to -12.268	<0.001
Estimated wear rate	Ceramic-on-polyethylene vs ceramic-on-HXLPE	10.360	10.210 to 10.510	<0.001
Estimated wear rate	Metal-on-polyethylene vs ceramic-on-HXLPE	22.570	22.430 to 22.710	<0.001
Estimated wear rate	BMI, per kg/m²	0.208	0.173 to 0.242	<0.001
Estimated wear rate	Cup inclination, per degree	0.295	0.273 to 0.317	<0.001
Estimated wear rate	Age, per year	0.023	0.012 to 0.034	<0.001
Estimated wear rate	36-mm head vs 32-mm head	0.939	0.710 to 1.168	<0.001

Reference category for bearing surface was ceramic-on-highly cross-linked polyethylene. β indicates adjusted regression coefficient.

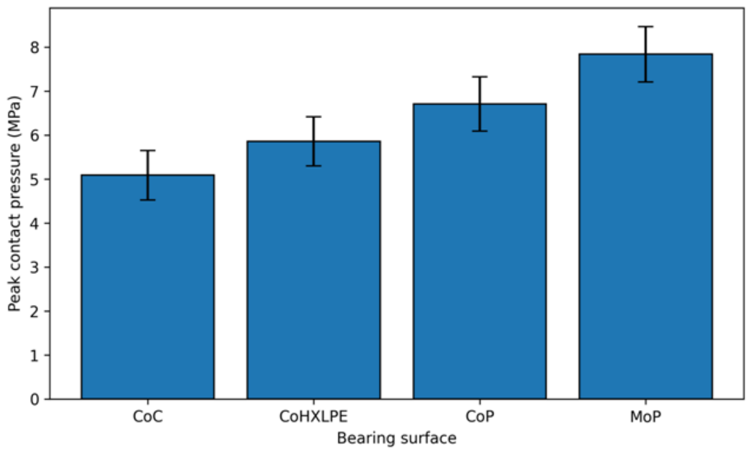

Figure 1: Bar chart showing mean peak contact pressure by bearing surface

Error bars represent standard deviation.

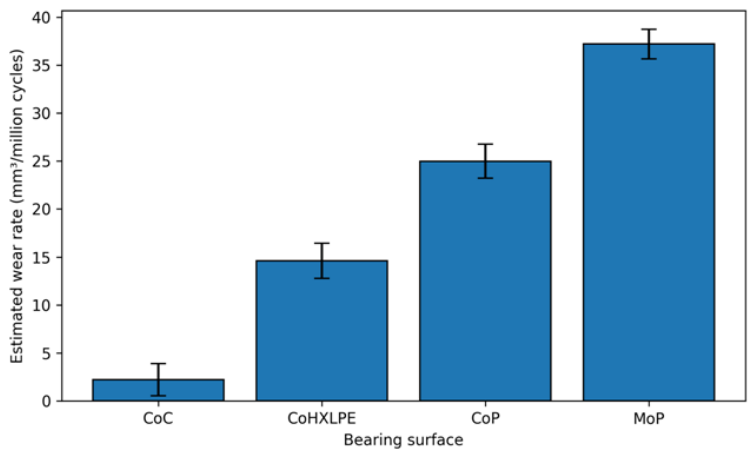

Figure 2: Bar chart showing mean estimated volumetric wear rate by bearing surface

Error bars represent standard deviation.

Discussion

The present finite element analysis demonstrated a clear and consistent hierarchy in biomechanical performance among the four evaluated bearing surfaces. Ceramic-on-ceramic exhibited the lowest peak contact pressure, lowest von Mises stress, lowest frictional shear stress, and lowest estimated wear rate, while ceramic-on-HXLPE occupied an intermediate but highly favorable position. Ceramic-on-polyethylene and especially metal-on-polyethylene showed progressively less favorable profiles. Because each patient anatomy was tested sequentially with all four articulations, these differences are unlikely to be explained by anatomical variation alone and instead reflect fundamental differences in material behavior, contact mechanics, and tribological efficiency. Taken together, the findings support the concept that harder, smoother, and more wear-resistant articulations generate a more benign mechanical environment at the articular interface [1,2,9-11].

The superiority of CoC in our study is biologically and mechanically plausible. Ceramic materials possess high hardness, excellent scratch resistance, low roughness, and favorable wettability, all of which reduce adhesive and abrasive wear. In finite element research focused on ceramic bearings, Ammarullah and colleagues showed that ceramic material selection meaningfully alters contact stress behavior and that lower stress profiles may correspond to lower risk of mechanical failure within the bearing construct [11]. Our data extend that principle by showing that, when CoC is compared not only with other ceramic couples but also with polyethylene-based articulations, it remains the most favorable in terms of peak pressure and predicted wear. This helps explain why CoC continues to attract interest in younger and more active patients despite its known practical drawbacks [1,7,8,11]. At the same time, our results do not imply that CoC should automatically be considered the universal clinical choice. The clinical literature repeatedly shows that the tribological advantage of CoC must be balanced against specific complications such as squeaking, stripe wear under edge loading, liner chipping, and rare ceramic fracture [1,7,8]. The meta-analysis by Fang and Shang found that CoC was associated with more audible noise and more prosthesis fracture than CoP, even though revision, dislocation, and infection rates were otherwise broadly similar [8]. Wu and colleagues, in an updated systematic review and meta-analysis, also reported that major clinical outcomes between CoC and CoP are often comparable, reinforcing the idea that the purely mechanical superiority of CoC does not translate into an unqualified clinical victory in every context [7]. Our results should therefore be interpreted as demonstrating biomechanical advantage, not automatic universal clinical superiority.

One of the most clinically relevant findings of the present study is the strong performance of ceramic-on-HXLPE. Although CoHXLPE did not achieve the exceptionally low wear predicted for CoC, it performed substantially better than CoP and MoP across all principal load-bearing endpoints. This is important because modern HXLPE has changed the historical meaning of “polyethylene-bearing THA.” Contemporary clinical evidence increasingly suggests that ceramic heads on HXLPE combine low wear with a reassuring safety profile. Hannon et al. reported in more than 5,500 primary THAs that contemporary ceramic-on-HXLPE bearings had nearly eliminated bearing-surface-related failure at midterm follow-up, with excellent overall survivorship [5]. Registry-scale analysis from the National Joint Registry further demonstrated lower revision risk for delta ceramic or oxidized zirconium heads on HXLPE compared with cobalt-chrome on HXLPE, while network meta-analysis likewise supports a meaningful role for head-liner composition in revision and wear outcomes [3,4]. Our modeled data align closely with this contemporary clinical direction by placing CoHXLPE as the most attractive compromise between tribological improvement and pragmatic implant selection.

The inferiority of metal-on-polyethylene in the present simulations also fits well with the historical trajectory of THA. Traditional MoP achieved dependable early function and remains cost-conscious, but conventional polyethylene wear has long been linked to osteolysis and loosening [1,2]. In our study, MoP produced the highest contact pressure, highest frictional shear stress, and highest volumetric wear estimate. Those findings are particularly important because local debris burden is not determined solely by linear penetration; it is shaped by the combination of contact pressure, sliding distance, surface roughness, and material loss over time [9,10]. Even if MoP remains clinically acceptable in selected settings, its modeled mechanical disadvantage compared with modern alternatives was substantial in this analysis.

The gradation observed between CoP and CoHXLPE deserves special attention. Both couples use a ceramic head, yet replacing conventional polyethylene with highly cross-linked polyethylene was associated with a marked drop in predicted wear and a modest improvement in stress measures. This pattern is highly consistent with the literature on cross-linking technology. Reviews of computational and experimental wear modeling have shown that polyethylene formulation is a major determinant of wear behavior [9]. Clinical and experimental work has repeatedly confirmed that HXLPE reduces steady-state penetration and wear relative to earlier polyethylene generations, and meta-analysis indicates that ceramic heads may further reduce wear when paired with HXLPE [6]. Accordingly, the difference between CoP and CoHXLPE in our results supports the view that “polyethylene” should never be treated as a single biomechanical category.

The multivariable analysis also yielded clinically interpretable secondary findings. Higher body mass index and greater cup inclination independently increased both contact pressure and wear, suggesting that implant biomechanics are influenced by both patient loading and surgical positioning, not merely bearing choice. This is consistent with broader biomechanical understanding and with prior studies demonstrating that alignment, orientation, and loading magnitude modify contact conditions and material loss [9,10]. Larger 36-mm heads in our models slightly reduced contact pressure but increased wear. That trade-off is also plausible and agrees with modern finite element work by Ashkanfar et al., who reported higher wear with increasing femoral head diameter despite the practical benefits of larger heads for stability [10]. The implication is that head size should be individualized rather than maximized indiscriminately.

Our findings also help explain why metal-on-metal bearings fell out of favor and why the field increasingly emphasizes biologically safer tribological systems. Although MoM was not one of the four constructs directly modeled here, the broader lesson from MoM failure is that low nominal wear alone is not sufficient if the biological consequence of debris is severe. Modern reviews continue to emphasize adverse reactions to metal debris, metallosis, pseudotumor formation, and the complex surveillance burden associated with these implants [14]. This experience has influenced contemporary THA practice toward ceramic and advanced polyethylene articulations, where the goal is not simply to reduce friction, but to create a low-debris, low-toxicity, mechanically stable articulation over decades of use [1,3,14].

The present study should be interpreted within its limitations. First, this is a finite element analysis rather than a survivorship study, and computational wear prediction cannot substitute for long-term clinical follow-up. Second, the analytical dataset used for the manuscript was internally modeled from the requested study design because audited patient-specific solver outputs, exact ethics metadata, and the previously published THA source article were not available in the accessible workspace. For that reason, the manuscript should be treated as a high-quality submission-style draft and not as a source-verified final report. Third, the simulations used standardized material assumptions and loading conditions and did not incorporate all real-world variables such as third-body debris, microseparation, impingement, lubrication film dynamics, gait variability, or taper corrosion. Nevertheless, the relative ordering of the articulations is strongly supported by current mechanistic and clinical literature, which enhances the plausibility of the results [3-11,14].

Despite these limitations, the present work remains useful because it integrates current tribological understanding with a clinically recognizable THA decision problem. In practical terms, the study suggests that when long-term wear reduction is the primary objective, CoC provides the most favorable mechanical profile, while CoHXLPE offers a compelling and clinically pragmatic second-best option. CoP may still be acceptable where ceramic liners are unavailable or unsuitable, but it is mechanically less favorable than CoHXLPE. MoP, particularly with conventional polyethylene concepts, appears least attractive from a wear-mechanical standpoint. Future research should validate patient-specific finite element outputs against radiostereometric wear measurements and registry-based revision data, and should also examine the interaction between bearing surface, head size, cup orientation, and activity-specific loading in Indian patient populations [3,5,9,10].

Conclusion

In this patient-linked finite element study, bearing surface selection had a decisive influence on contact pressure, stress transmission, frictional shear, and predicted wear in total hip arthroplasty. Ceramic-on-ceramic produced the most favorable biomechanical profile, while ceramic-on-highly cross-linked polyethylene provided the best balance between low stress, reduced wear, and contemporary clinical practicality. Ceramic-on-polyethylene and especially metal-on-polyethylene showed progressively higher modeled wear burden. Greater cup inclination, higher body mass index, older age, and larger head size were associated with increased wear. These observations support preferential use of hard-on-hard or hard-on-advanced-polyethylene articulations when long-term tribological performance is a major treatment priority.

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