

Biomechanical and Functional Performance of Hip Prosthesis Materials in Total Hip Arthroplasty: A Systematic Review

Avani Braz de Souto Filho ¹, Carlos Felype de Oliveira Pena ¹, Murilo Martins Veras Neto ¹, Luiz Eduardo Sampaio Duarte ¹, Karine Kelly Rangel de Andrade Monte ¹, Carolina Pereira Vieira ², Mário Augusto Silva Pereira ³, João Gabriel Ventura Bariani ³, Mateus Ribeiro Oliveira ³, Weiler Ferreira Fonseca ³, Heytor Mendes Camargo Costa ⁴, Luiz Fernando Sari Sampaio ⁴, Fernanda Grazielle da Silva Azevedo Nora ⁵

¹ Department of Orthopedics and Traumatology, IJF - Instituto Doutor José Frota, Fortaleza, CE, Brazil

² Department of Orthopedics and Traumatology, IOG - Instituto Ortopédico de Goiânia, Goiânia, Goiás, Brazil

³ Department of Orthopedics and Traumatology, HUGO - Hospital de Urgências de Goiânia, Goiânia, Goiás, Brazil

⁴ Department of Orthopedics and Traumatology, HEAPA - Hospital Estadual de Aparecida de Goiânia, Aparecida de Goiânia, Goiás, Brazil

⁵ Faculty of Physical Education and Dance, UFG - Universidade Federal de Goiás, Goiânia, Goiás, Brazil

*Correspondence: Fernanda Grazielle da Silva Azevedo Nora (fernanda_nora@ufg.br)

How to cite this paper:

Souto Filho, A. B. de, Oliveira Pena, C. F. de, Neto, M. M. V., Duarte, L. E. S., Andrade Monte, K. K. R. de, Vieira, C. P., Pereira, M. A. S., Bariani, J. G. V., Oliveira, M. R., Fonseca, W. F., Costa, H. M. C., Sampaio, L. F. S., & Silva Azevedo Nora, F. G. da. (2025). Biomechanical and Functional Performance of Hip Prosthesis Materials in Total Hip Arthroplasty: A Systematic Review. *Global Journal of Orthopedics*, 1(1), 51–59. DOI: 10.31586/gjo.2025.6111

Received: April 11, 2025

Revised: May 26, 2025

Accepted: June 3, 2025

Published: June 11, 2025



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Abstract: This systematic review aimed to evaluate the biomechanical properties, functional performance, and clinical outcomes of different hip prosthesis materials and designs used in total hip arthroplasty (THA). A comprehensive search strategy identified 34 peer-reviewed studies published between 2015 and 2024. The materials investigated included cobalt-chromium-molybdenum (CoCrMo), titanium alloys, PEEK, ceramics, and advanced surface coatings such as polycrystalline diamond (PCD). In addition, dual mobility systems, lattice structures, and additively manufactured and patient-specific implants were assessed. The studies utilized clinical trials, finite element analysis, and biomechanical testing to compare outcomes such as wear resistance, stress distribution, osseointegration, and range of motion. The findings demonstrated that titanium alloys and porous lattice structures reduce stress shielding, while ceramics and CoCrMo provide superior wear resistance. Dual mobility implants improved joint stability and range of motion, particularly in high-risk patients. PEEK and PCD showed promising properties but lacked robust long-term data. The integration of advanced manufacturing technologies and material innovations has led to more personalized and biomechanically efficient solutions for THA. Further longitudinal studies are needed to validate these developments. This review provides a critical synthesis of the biomechanical, functional, and clinical implications of contemporary hip prosthetic systems.

Keywords: Total Hip Arthroplasty, Biomechanics, Prosthesis Materials, Dual Mobility, Additive Manufacturing

1. Introduction

Total hip arthroplasty (THA) remains one of the most successful and commonly performed orthopedic procedures worldwide, providing significant improvements in pain, function, and quality of life for patients with advanced hip joint pathology [1-3]. Over the past decades, the evolution of hip prosthesis design has been marked by critical advancements in biomaterials, surface modifications, articulating mechanisms, and surgical techniques [4-6]. The optimization of biomechanical properties and implant

functionality continues to be a central goal in improving the longevity and performance of hip prostheses.

The biomechanical success of a prosthesis depends on the appropriate selection of materials that match the mechanical properties of native bone and provide long-term resistance to fatigue, wear, and corrosion [7,8]. Cobalt-chromium-molybdenum (CoCrMo) alloys have been widely used due to their high strength and wear resistance, although concerns regarding stress shielding have prompted the exploration of titanium alloys and polymer-based alternatives [9-11]. Titanium alloys, with their lower elastic modulus and high biocompatibility, offer improved osseointegration and more physiological load transmission [12-14].

Recent interest has shifted toward high-performance polymers such as polyetheretherketone (PEEK) and composites like CFR-PEEK, which exhibit favorable biomechanical compatibility with cortical bone and enhanced imaging characteristics due to their radiolucency [9,10]. While promising in preclinical models, these materials require further long-term clinical validation before they can be adopted broadly in THA practice [15,16].

In addition to the base material, surface treatments such as polycrystalline diamond (PCD) coatings have been explored to enhance wear resistance and reduce friction at the bearing interface [10,32]. These coatings have demonstrated excellent tribological performance under simulated joint conditions but remain limited by cost and manufacturing complexity.

The tribological performance of articulating surfaces plays a crucial role in implant longevity. Ceramic-on-ceramic (CoC) and ceramic-on-polyethylene (CoP) pairings have gained traction due to their low wear rates, biological inertness, and favorable clinical outcomes, particularly in younger, more active patients [11,12,19,20]. Despite their advantages, concerns remain regarding mechanical noise (e.g., squeaking) and brittleness in CoC configurations [19,20].

Functional performance and joint stability are strongly influenced by implant design. Dual mobility systems have become increasingly popular in revision and high-risk primary THA due to their enhanced range of motion (ROM) and reduced dislocation risk [13,14,24]. These implants integrate a small inner bearing and a larger polyethylene liner, facilitating improved kinematics and better head-to-neck ratios.

Additive manufacturing (AM) has revolutionized implant design, allowing for the creation of lattice and triply periodic minimal surface (TPMS) structures that promote bone ingrowth and enhance initial mechanical stability [17,28,30]. This technology has also enabled the production of patient-specific implants that match anatomical and biomechanical demands more precisely, reducing micromotion and optimizing stress distribution [20,30,31].

Postoperative outcomes are influenced not only by implant properties but also by surgical approach, rehabilitation strategies, and perioperative protocols. Minimally invasive techniques and enhanced recovery after surgery (ERAS) programs, including multimodal analgesia and early mobilization, have demonstrated improvements in functional recovery and reduced complication rates [22,23,24,26]. Regional studies comparing structured rehabilitation protocols further highlight the influence of healthcare infrastructure on long-term outcomes [25,27].

Wear simulations, clinical trials, and registry data collectively inform prosthesis selection by correlating biomechanical performance with patient-reported outcomes and revision rates. The integration of artificial intelligence in implant design and the application of robotic-assisted surgery are further refining precision and personalization in THA [29,30].

Given the continuous development of materials and technologies, a comprehensive synthesis of current evidence is necessary to guide clinical decisions. The aim of this systematic review is to compare the biomechanical performance, functional outcomes,

and clinical implications of different hip prosthesis materials and designs. The review incorporates findings from 34 peer-reviewed studies, focusing on the relationship between material selection, implant biomechanics, and long-term functional success in total hip arthroplasty.

2. Methodology

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring transparency, reproducibility, and methodological rigor throughout all review stages. The protocol included the following steps: formulation of the research question, development of eligibility criteria, systematic literature search, study selection, data extraction, quality assessment, and synthesis of results.

2.1. Research Question and Objective

The guiding research question was: "What are the biomechanical characteristics, functional performance outcomes, and clinical applications of different hip prosthesis materials and designs in total hip arthroplasty (THA)?" The objective was to compare evidence regarding the mechanical performance, osseointegration potential, tribological behavior, and patient-specific outcomes of CoCrMo, titanium alloys, ceramics, PEEK, dual mobility systems, and 3D-printed prostheses.

2.2. Eligibility Criteria: Inclusion Criteria

- Peer-reviewed full-text articles published in English from January 2015 to March 2024.
- Studies reporting original data on biomechanical, functional, or clinical aspects of hip prosthesis materials and/or designs.
- Experimental (in vitro, in silico), clinical (prospective, retrospective, RCTs), and cohort studies.
- Studies using human subjects or human-relevant mechanical models (e.g., cadaveric, FEA).

Exclusion Criteria:

- Editorials, opinion papers, letters to editors, and non-peer-reviewed material.
- Review articles without primary data.
- Studies focusing solely on acetabular revisions or pediatric implants.

2.3. Information Sources and Search Strategy

Systematic searches were conducted in PubMed, Scopus, Web of Science, ScienceDirect, and SpringerLink databases. Grey literature and cross-referenced citations were screened to supplement the search. Search terms included: "hip prosthesis," "total hip arthroplasty," "biomechanics," "prosthetic materials," "CoCrMo," "titanium alloy," "PEEK," "ceramic," "dual mobility," "3D printing," "finite element analysis," and "functional outcome." Boolean operators and filters were applied to enhance precision.

2.4. Study Selection

All identified articles were exported to reference management software and screened by two independent reviewers. First, duplicates were removed. Then, titles and abstracts were evaluated for relevance. Articles meeting inclusion criteria were subjected to full-text review. Disagreements were resolved through discussion or adjudicated by a third reviewer.

2.5. Data Extraction

A standardized data extraction form was used to collect information on study design, sample size, implant type, material composition, biomechanical testing protocols, mechanical results (e.g., Young's modulus, fatigue strength, wear rates), functional outcomes (e.g., Harris Hip Score, range of motion), and complications (e.g., dislocation, implant loosening).

2.6. Quality Assessment

Quality and risk of bias were independently assessed using tools tailored to study type: Modified Coleman Methodology Score for clinical studies, STROBE checklist for observational studies, and a custom grading system for finite element and materials engineering studies. Each study was scored and ranked as high, moderate, or low methodological quality.

2.7. Data Synthesis

Data were synthesized narratively and presented in thematic categories aligned with the review objectives: (1) biomechanical properties by material type; (2) wear behavior and tribology; (3) functional and clinical outcomes by design; (4) innovations in manufacturing and customization. A summary comparison table (Table 1) was developed to consolidate biomechanical findings.

2.8. Study Inclusion Summary

A total of 34 studies met all inclusion criteria and were included in the final synthesis. These studies collectively represent a wide range of methodologies, prosthesis types, and clinical settings, providing a robust evidence base to support conclusions about the comparative performance of modern hip prostheses. The primary objective was to identify, appraise, and synthesize the biomechanical, functional, and clinical performance data on various hip prosthesis materials and designs reported in peer-reviewed literature.

3. Results

Table 1 summarizes key comparative findings from the 34 reviewed studies and provides a structured overview of hip prosthesis materials and designs, focusing on their biomechanical performance. It enables a side-by-side comparison that supports evidence-based selection of the most appropriate prosthesis for various clinical contexts.

Table 1. Types of Hip Prostheses.

Material/Design	Biomechanical Advantages	Limitations	References
CoCrMo	High strength, superior wear and fatigue resistance	High elastic modulus, stress shielding	[1,2,5,18]
Titanium Alloys	Low modulus, high biocompatibility, osseointegration	Less wear resistance than CoCrMo	[6,7,15,16]
PEEK	Bone-like modulus, radiolucency, reduces stress shielding	Limited clinical long-term data	[9,10]
PCD Coatings	Optimal stress distribution, high hardness, low friction	High manufacturing cost	[10,32]
CoC Bearings	Low wear, inert, ideal for young/active patients	Potential for squeaking, higher cost	[11,12,19,20]
CoP Bearings	Lower wear than MoP, improved patient-reported outcomes	Still releases some particles	[19,24]
Dual Mobility	Enhanced ROM, prevents dislocations, good long-term survival	Increased acetabular volume required	[13,14,19,24]
Lattice Structures	Better load distribution, promotes osseointegration	Requires advanced manufacturing processes	[17,28,30]
Additive Manufacturing	High customization, precise anatomical matching	Cost, technical complexity	[20,30,31]

Patient-specific Implants	Improved fit, reduced impingement and revision risk	Requires imaging and custom planning	[21,30]
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CoCrMo (Cobalt-Chromium-Molybdenum) alloys offer high wear resistance and durability, ideal for active patients requiring strong load-bearing implants, although their high stiffness can lead to stress shielding and bone resorption. Titanium alloys, such as Ti-6Al-4V and Ti-35Nb-5Ta-7Zr, present better elastic compatibility with bone and promote osseointegration, despite lower tribological performance compared to CoCrMo.

PEEK (Polyetheretherketone) has demonstrated promising outcomes due to its bone-like elasticity and radiolucency, facilitating post-operative imaging and reducing bone resorption; however, its clinical validation over the long term is still limited. PCD (Polycrystalline Diamond) coatings ensure excellent surface hardness and reduced friction, making them suitable for articulating surfaces, albeit at increased manufacturing cost.

CoC (Ceramic-on-Ceramic) bearings minimize wear debris and inflammation, with excellent long-term survivorship, particularly in young, active individuals, but risks include component squeaking and fracture. CoP (Ceramic-on-Polyethylene) combinations offer a balance of reduced wear and improved clinical scores, though polyethylene wear particles can still pose a challenge.

Dual mobility systems have become highly effective in preventing dislocations and improving ROM, particularly beneficial for elderly or neurologically impaired patients. Nevertheless, they require more acetabular space. Lattice-based structures and implants produced via additive manufacturing improve stress distribution and biological fixation but involve high cost and technical expertise. Patient-specific implants improve anatomical fit and postoperative biomechanics but demand sophisticated imaging and planning.

The biomechanical superiority of hip prostheses is not determined solely by material properties but also by implant geometry, articulation design, fixation methods, and perioperative care. CoCrMo and titanium remain robust choices, while PEEK and ceramics offer compelling alternatives. Dual mobility designs consistently outperform others in terms of stability and functional range, particularly in complex or high-risk cases. The integration of AI-based design, personalized imaging, and advanced rehabilitation regimens is reshaping the landscape of hip arthroplasty towards more predictable and patient-centered outcomes.

4. Discussion

The biomechanical integrity and functional outcomes of total hip arthroplasty (THA) are closely tied to the material properties, design geometry, and manufacturing techniques of hip prostheses. This systematic review of 34 peer-reviewed studies elucidates key factors contributing to the performance and limitations of contemporary hip implants. A comprehensive synthesis of these investigations reveals that the biomechanical behavior of prostheses is not solely governed by material strength or fatigue resistance but requires a multifactorial optimization of modulus compatibility, tribological performance, and structural integration.

Cobalt-chromium-molybdenum (CoCrMo) alloys have historically been regarded as the biomechanical benchmark in THA due to their exceptional wear resistance and high strength-to-weight ratio [1,2,5,18]. Studies employing finite element analysis and clinical follow-up confirm their longevity under cyclic loading and in high-demand patient populations. However, the high elastic modulus of CoCrMo significantly exceeds that of cortical bone, inducing stress shielding and consequent bone resorption, particularly in the proximal femur [6]. These biomechanical drawbacks underscore the importance of material modulus compatibility in long-term implant success.

In contrast, titanium-based alloys such as Ti-6Al-4V and beta-phase compositions like Ti-35Nb-5Ta-7Zr exhibit a more bone-conforming elastic modulus and higher corrosion resistance [7,15,16]. Their biomechanical profile supports more physiological stress transfer to surrounding bone, promoting osseointegration and reducing the risk of aseptic loosening. Nevertheless, these materials exhibit lower tribological performance, necessitating optimized surface treatments or articulation pairings to reduce wear [6,7]. The evidence supports titanium as the material of choice for femoral stems in osteoporotic patients or those requiring cementless fixation [15,16].

Emerging polymer-based materials, including polyetheretherketone (PEEK) and carbon fiber reinforced PEEK (CFR-PEEK), have been investigated for their favorable elastic properties and radiolucency [9]. These materials closely approximate the mechanical properties of cortical bone, thereby minimizing stress shielding and allowing better periprosthetic bone preservation. Several computational studies demonstrate that PEEK reduces strain concentrations in the femur by more than 100% when compared with conventional titanium stems [10]. However, a lack of long-term clinical validation limits its immediate integration into routine clinical use.

High-performance ceramic materials, including zirconia-toughened alumina (ZTA) and silicon nitride (Si_3N_4), have shown superior tribological behavior in wear simulation studies [11,12]. Their use in ceramic-on-ceramic (CoC) configurations minimizes particulate debris, thereby reducing the incidence of osteolysis. Although CoC is ideal for younger, high-activity patients [19,20], risks of squeaking, component fracture, and elevated manufacturing costs temper their universal application. Conversely, ceramic-on-polyethylene (CoP) combinations offer lower wear than traditional metal-on-polyethylene (MoP) and better functional scores, though polyethylene wear debris remains a clinical concern [19,24].

A noteworthy advancement in enhancing prosthetic ROM and stability is the implementation of dual mobility systems. These configurations, which combine a mobile polyethylene liner with a stable metal shell, have demonstrated superior biomechanical performance in preventing dislocations and increasing joint mobility in high-risk and revision scenarios [13,14,19,24]. While dual mobility increases the volume of the acetabular construct, multiple registry studies affirm its favorable performance in both primary and complex THA cases.

Recent interest has focused on lattice-structured and TPMS-based implants produced through additive manufacturing. These designs facilitate stress redistribution and bone ingrowth while maintaining lightweight architecture [17,28,30]. The porous topology allows for graded mechanical properties that mimic native bone, thereby enhancing initial stability and long-term integration [20,31]. Furthermore, patient-specific implants generated from CT imaging data have demonstrated superior biomechanical adaptation in patients with abnormal femoral morphology, with studies showing improved load alignment and reduced micromotion at the bone-implant interface [21,30].

Wear simulation and retrieval studies underscore the importance of tribological optimization. For instance, combinations of CoCrMo with UHMWPE yielded the lowest volumetric wear rates under gait-cycle loading, with some studies reporting wear volumes as low as $0.004 \mu\text{m}^3$ over 10 cycles [18]. PCD-coated articulations also demonstrate minimized frictional losses and maximal resistance to surface deformation, although their widespread use is limited by manufacturing costs and a lack of high-quality clinical data [10,32].

Surgical techniques and perioperative protocols significantly impact implant biomechanics postoperatively. Minimally invasive approaches, such as the direct anterior and posterior techniques, were associated with better alignment, lower soft tissue trauma, and faster recovery times compared to lateral or transtrochanteric methods [22]. Integration of robotic systems and navigation tools improved component orientation, thereby reducing impingement risk and optimizing load distribution [30,31].

Lastly, functional recovery is influenced by postoperative care. ERAS protocols, including early mobilization and multimodal analgesia (e.g., subanesthetic esketamine), contribute to improved early functional scores and reduced systemic inflammation [23,24,26]. Rehabilitation strategies, especially in structured programs like those in Germany, demonstrate better mobility outcomes and adherence to evidence-based exercise regimens compared to less structured systems [25,27].

Additionally, prosthesis fixation techniques such as press-fit, cemented, or hybrid approaches must be aligned with the biomechanical profile of the implant material. Titanium-based stems show superior results in cementless applications due to their surface affinity for bone and capacity for osseointegration [7,16]. Conversely, CoCrMo, while mechanically robust, often necessitates cemented fixation to mitigate stress shielding. These considerations are critical for tailoring treatment to patient-specific skeletal conditions and bone mineral density profiles.

The long-term success of hip prostheses also depends on the synergy between the prosthesis design and dynamic gait loading. Studies employing FEA simulations have demonstrated that lattice and TPMS-based stems distribute loading more evenly across the diaphyseal and metaphyseal regions, potentially reducing localized bone remodeling and mechanical failure [17,28,30]. The use of AM enables the design of these intricate porous architectures, although their fatigue behavior under real-life ambulatory loading still requires long-term validation.

From a clinical perspective, outcomes such as dislocation rates, component loosening, and periprosthetic fractures are heavily influenced by the biomechanical integrity of the prosthesis system. Dual mobility implants, for instance, offer a demonstrable reduction in dislocation risk in both primary and revision cases [13,14,24]. CoC and CoP bearings continue to perform well in registry studies regarding component survival and patient-reported function, albeit with distinct complication profiles linked to their tribological properties [19,24].

One of the less addressed but important aspects in the literature is the environmental and economic sustainability of different implant systems. Materials like PEEK and patient-specific AM constructs, while biomechanically promising, incur higher costs and carbon footprints compared to conventional metallic options [30,31]. Future research must integrate cost-effectiveness and life cycle analysis into implant selection algorithms to ensure their feasibility in universal healthcare systems.

Another critical dimension in the evaluation of hip prosthesis materials is their interaction with biological tissues at the cellular level. Titanium alloys, due to their passive oxide layers and favorable surface energy, promote better osteoblast adhesion and proliferation compared to CoCrMo and PEEK, which may not inherently support cellular response without surface modifications [6,7]. Surface engineering techniques such as plasma spraying, hydroxyapatite coatings, and nanoscale texturing have been used to enhance bioactivity and ensure robust bone-implant integration [3,8]. These approaches are especially relevant in elderly patients or those with compromised bone healing potential.

In addition to mechanical considerations, the wear particle profile of each material has significant clinical implications. For instance, UHMWPE and conventional polyethylene generate wear debris that can activate macrophages and osteoclasts, leading to periprosthetic osteolysis [18,19]. Crosslinked polyethylene and antioxidant-stabilized versions have shown reductions in volumetric wear and biological reactivity. Meanwhile, CoC bearings, while producing negligible particulate matter, have a distinct failure profile involving edge loading and squeaking, necessitating precise surgical technique and component orientation [12,19,20].

Furthermore, studies have suggested that differences in material stiffness influence peri-implant bone remodeling patterns. PEEK and porous titanium structures have been associated with more homogeneous load transmission, which reduces proximal stress

shielding and maintains femoral bone stock [9,10,17]. This is particularly important in young patients who may require revision surgery decades later, as preserved bone quality facilitates future implant anchorage and reduces surgical morbidity.

Biomechanical studies also show that stem design significantly influences torsional and axial stability. Short-stem and anatomic designs, often fabricated from titanium alloys, are biomechanically favorable in conserving proximal bone while maintaining fixation stability [15,16]. However, their clinical performance is dependent on precise preoperative templating and intraoperative execution. Misalignment or undersizing can result in early loosening or periprosthetic fractures, particularly in osteoporotic bone.

Finally, the long-term follow-up of patient-specific and additively manufactured implants must include not only mechanical endurance but also their biological integration and adaptability over time. Initial reports are promising, with customized implants demonstrating excellent congruency, reduced implant migration, and early functional gains [21,30,31]. Yet, comparative trials are necessary to determine whether these advantages translate into superior survivorship and cost-efficiency. As the field advances, such technologies will likely benefit from integration with real-time intraoperative data and artificial intelligence tools to enhance planning, precision, and personalization of total hip arthroplasty.

5. Conclusion

This systematic review sought to evaluate the biomechanical behavior, functional performance, and clinical applicability of hip prostheses based on 34 selected studies. The findings demonstrate that the selection of prosthetic materials, articulating surfaces, and design geometry directly influences mechanical integrity, biological integration, and long-term survivorship in total hip arthroplasty. Cobalt-chromium-molybdenum (CoCrMo) alloys remain preferred for high-strength applications, whereas titanium-based alloys offer superior bone compatibility and osseointegration, especially in cementless configurations. Novel polymers such as PEEK and surface-enhanced materials like PCD show biomechanical promise but require more clinical validation.

Ceramic bearings, particularly ceramic-on-ceramic (CoC) and ceramic-on-polyethylene (CoP), provide enhanced tribological properties with reduced wear particle generation. Dual mobility systems significantly improve joint stability and range of motion, making them effective in high-risk patients. Additive manufacturing and patient-specific implants contribute to better anatomical congruence and load distribution, though high costs and technical demands remain limiting factors.

Therefore, the optimal choice of hip prosthesis is multifactorial and must be tailored to the patient's age, bone quality, anatomical features, and activity level. No single solution is universally superior; rather, successful outcomes depend on the biomechanical compatibility between material properties, implant geometry, surgical precision, and postoperative care. As innovations in materials science and personalized medicine evolve, further longitudinal studies are essential to validate these approaches and guide their integration into routine orthopedic practice.

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