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BIOMECHANICAL ASSESSMENT OF WEAR IN CERAMIC ON CERAMIC AND CERAMIC ON XLPE THAs

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Total Hip Arthroplasty (THA) is an effective treatment for severe hip arthritis, with patients reporting high rates of satisfactory results postoperatively. There are a variety of choices regarding THA implant designs. Ceramic on Ceramic and Ceramic on Highly Cross-Linked Polyethylene (XLPE) THAs are the materials of choice nowadays. The purpose of this study is to review the effect of kinematics and kinetics on wear (*in vivo* and *in vitro* testing) that affect wear in Ceramic on Ceramic and Ceramic on XLPE total hip arthroplasties and identify possible advantages amongst them. The study hypothesis was that THA kinematics and/or kinetics, since they directly affect THA wear, could provide data for possible advantages between the examined implant designs. A systematic review of the literature identified no significant evidence for biomechanical advantages between these two prostheses in terms of wear. Further research is proposed with the use of gait analysis systems combined with surface electromyography to further investigate THA biomechanics at a laboratory set up. Wearable

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sensors technology could also identify detailed biomechanical parameters in more complex daily activities.

Keywords: THA biomechanics; total hip arthroplasty wear; ceramic on ceramic THA kinematics; ceramic on XLPE THA kinetics; THA *in vivo* wear; hip arthroplasty *in vitro* wear.

1. Introduction

Total hip arthroplasty (THA) is among the orthopaedic surgeries considered to be most successful. Patients refer high satisfaction rates and radical improvement in the quality of life postoperatively.[1,2]

For an artificial hip joint construction, there is a compromise in material selection, bearing in mind friction issues, corrosion environment, biocompatibility, and implant longevity. The various components of the total hip replacement (THR) must meet specific mechanical criteria to successfully withstand the compressive loads developed in the joint and transfer the continually changing and repetitive forces caused by gravity and muscular action. Therefore, strength, elasticity, toughness, and ductility are essential material characteristics.[3,4]

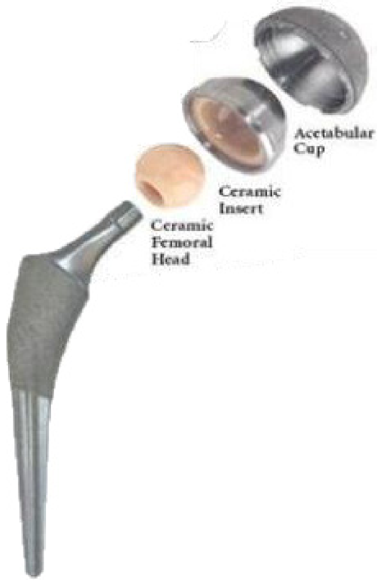
The biomechanics of THA depend on prosthesis design, bearing surface and lubrication characteristics and fixation method. Their designs include femoral component cemented or press-fit (uncemented-tapered stems, extensively porous coated stems and modular stems) and the acetabular components, cemented (polyethylene, metal) or press-fit (uncemented-metal). The bearing surfaces usually consist of polyethylene, metal or ceramic.

Prerequisite features for the articulating surfaces of THR prostheses are low friction and wear. In addition to different modes of wear, the implant materials also degrade in different ways in the very corrosive environment of the body fluids.[5] Research interest nowadays focuses on identifying possible advantages and disadvantages of two main implant designs, Ceramic on Ceramic and Ceramic on Highly Cross-Linked Polyethylene (XLPE) THAs.

Wear problems reported with the metal-on-metal and the metal-on-polyethylene (metal-on-PE) artificial joints lead to the introduction of ceramics. Its high level of oxidation makes it a material very well tolerated.

The French surgeon Pierre Boutin performed the first alumina-on-alumina THA in April 1970.[6] Since then, the progress in materials and methods contributed to increasing survival of the cup and stem at 20 years, reducing periprosthetic cystic or scalloped lesions, fractures of the alumina socket or head, and occurrence of osteolytic lesions.[7]

THR is still a controversial surgery for active patients of younger age, since wear instability, loosening, or other mechanical failures dramatically increases the probability of revision surgery needed.[8,9] A key factor concerning the durability of a total hip prosthesis is periprosthetic osteolysis, and according to studies, wear and the number of debris particles produced in the joint greatly affects it.[10,11] It has been reported that ceramic on ceramic (CoC) prostheses have high wear resistance and, therefore, produce less wear debris.[12]



Over the past decade, CoC bearings have gained significant popularity. *In vitro* experiments have shown advantages of CoC bearings compared to ceramic on polyethylene (CoP) in terms of wear rates and osteolytic potential.[13] Their disadvantages, however, include squeaking sounds and increased fragility compared to polyethylene (PE).[14] There has been concern regarding the increased use of CoC-THA as an alternative to contemporary CoP-THA, and the choice remains controversial.[15]

Highly XLPE components were introduced in THR surgery in 1998,[16] and by 2003 XLPE was used in 65% of THRs in the United States.[17] More recently, in Australia, the 2015 annual report of the joint replacement registry reported that XLPE represented 95% of all primary THRs incorporating a PE bearing.[18] XLPE has been the material of choice in 174,409 procedures reported to the AOANJRR up until 2015.[18] Of the 33,954 primary THRs undertaken in Australia in 2015, 68% involved an XLPE bearing surface against either ceramic (25%) or ceramicised metal (7%) femoral head.[18] Similar percentages apply worldwide.

According to the Australian Registry, oxidized zirconium (Oxynium)/XLPE is the bearing surface with the highest survival at 10 years as it produced significantly less wear.[19] Still, this result should be cautiously interpreted, the reason being that it is a single company's product, used in a small number of cases, so more reliable data are required for long-term outcomes. The option of choice in elderly patients or younger patients without a correct anatomical positioning of the acetabular component has been ceramic heads with XLPE liners.

Wear in the aforementioned THAs is of great importance for the longevity of these implants. Several factors that affect wear (CoC squicking, CoC better behavior *in vitro* testing, body fluids, etc.) are still controversary. The effect and possible advantages of biomechanical (kinematics and kinetics) concept of hard on hard and hard on soft THA wear is still unclear.

Thus the purpose of this study is to review the effect of kinematics and kinetics on wear (*in vivo* and *in vitro* testing) that affect wear in Ceramic on Ceramic and Ceramic on XLPE total hip arthroplasties and identify possible advantages amongst them. The study hypothesis was that THA kinematics and/or kinetics, since they directly affect THA wear, could provide evidence for possible advantages between the examined implant designs. Such evidence could be used for further research by biomechanists in order to improve THA implants' wear behavior, which could lead in improved wear rates. The provided information could also help orthopedic surgeons with their decision making when the wear rate is the key factor of interest.

2. Methodology

2.1. *Search strategy design*

The keywords used for the review were selected to assess THA biomechanics and wear responses to load, THA wear as a result of biomechanical factors (kinematic or/kinetic), and examination of wear for CoC or/and CoXLPE THAs. The database search lasted six months from November 2018 till March 2019. The range of publication dates where studies collected was from 1995 till 2018. Quotation marks were used to ensure the appearance of the keywords at the manuscripts. Following the recording of all the titles, abstracts and reference lists were examined for relevant studies as well. Before the first level screening, the copies of the recorded results were removed. The studies that met the inclusion criteria of the first level screening were recorded (four months process) and passed to the second level of the study selection process. Following the completion of the second level screening, the full text was carefully evaluated (lasted for three months). Two independent reviewers implemented the research strategy, as described in detail at the data collection process section. The manuscripts included in this review were examined for the risk of bias using the GRADE tool and was critically discussed.

2.2. *Strategy of bibliography-information sources*

The literature reviewed in PubMed, Medline, Google Scholar, and Science Direct databases, using relevant keywords and key phrases to identify and record corresponding studies. We used Medical Subject Headings terms and free words, including THA biomechanics, THA wear, ceramic on ceramic THA, ceramic on ceramic wear, ceramic on XLPE wear, ceramic on XLPE THA, total hip implant biomechanics and wear, THR kinematics and kinetics. In addition to databases, searching of reference lists was conducted as well.

2.3. *Eligibility-inclusion and exclusion criteria*

The studies proceeded to qualitative analysis only if they met the following inclusion criteria: They were published in English, peer-reviewed, assessed wear in THAs, refer biomechanical issues that affect wear in CoC and CoXLPE, correlate kinematic and kinetic parameters to THA wear, assessed wear in CoC or/and CoXLPE total hip implant designs *in vitro* as well *in vivo*.

Papers were excluded if: they were case studies, not peer-reviewed, did not evaluate biomechanical parameters and their results to wear, referred wear issues as a result of other than kinematic or kinetic factors, they did not study at least CoC or/and CoXLPE THAs.

2.4. *Study selection process*

The first level screening comprised of evaluation of titles and abstracts of the literature concerning the eligibility criteria set at the search strategy design. The selected studies passed at the second level of screening, which involved a critical assessment of the full text. Each study was evaluated based on meeting the purpose of this review and the inclusion criteria, presenting accurate data important for this study that concern wear at CoC or/and CoXLPE THAs.

2.5. *Data collection process*

The titles and abstracts of papers found in the database search were evaluated individually by two reviewers. The same researchers assessed the full text of selected papers. Disputes over membership and/or exclusion were resolved by consensus. The lists of included and excluded studies were then discussed with the advisory group for the final decision. In order to identify the data of interest for extraction, we designed tables listing all papers included.

We categorized data according to a "yes/no fixed text" reply, or free text in cases where the fixed text was not applicable. All these data recorded to electronic forms -excel spreadsheets.

During the data collection process, the first researcher extracted the data, and the second independently checked the data extraction forms for accuracy and details.

The general information used during the data extraction process was the registration of the researcher performing data extractions and the date. Identification features of the study processed included the research team names, the study title and its full citation, the type of publication (only included journal articles), and the source of funding if existed.

Table 1. Assessment of risk of bias.

Outcomes	No. of participants (studies)	Quality of evidence
In vivo THA biomechanics and wear	552 (10 Studies)	⊕ ⊕ ⊕⊕ HIGH
THA wear after *in vitro* testing of biomechanical factors	*In vitro* testing (11 Studies)	⊕ ⊕ ⊕⊕ HIGH
Wear for CoC or/and CoXLPE THAs through clinical factors	4592 (3 Studies)	⊕ ⊕ ⊕⊕ HIGH

The objectives of the included studies, their design, and the inclusion and exclusion criteria applied declared as study characteristics. These characteristics were recorded to control whether they met the eligibility criteria of our total hip implant designs review. The kinematic (Range of motion) and kinetic parameters (force loading, joint moments) assessed in each study to identify their impact on THAs' wear.

Data extraction forms were created on a sample of the included studies to ensure that the captured information was relevant and to avoid extracting unrequired data. The consistency of the data obtained was assessed to eliminate data extraction errors.

2.6. *Data items*

Following the data collection process, the items found and included at this review were studies that assess THA biomechanics and wear responses to load, THA wears as a result of biomechanical factors (kinematic or/kinetic) and examination of wear for CoC or/and CoXLPE THAs.

2.7. *Risk of bias in individual studies*

We used the Grading of Recommendations Assessment, Development and Evaluation tool (GRADE) for a "study-level" to assess the risk of bias. The risk of bias in individual studies included in this systematic review is low. According to GRADE, the strength of evidence was high for *in vivo* and *in vitro* studies that assess clinical findings of biomechanical factors that affect wear in THAs (Table 1).

3. Results

3.1. *Study selection*

The search strategy retrieved 1422 potentially relevant papers, of which 1191 through database searching and 231 by references to related papers. 1203 papers went to the next stage for further examination after removing the copies. The first level of screening assessed the titles and abstracts of the literature search results, and 550 papers were excluded for not meeting the eligibility criteria determined by the research methodology.

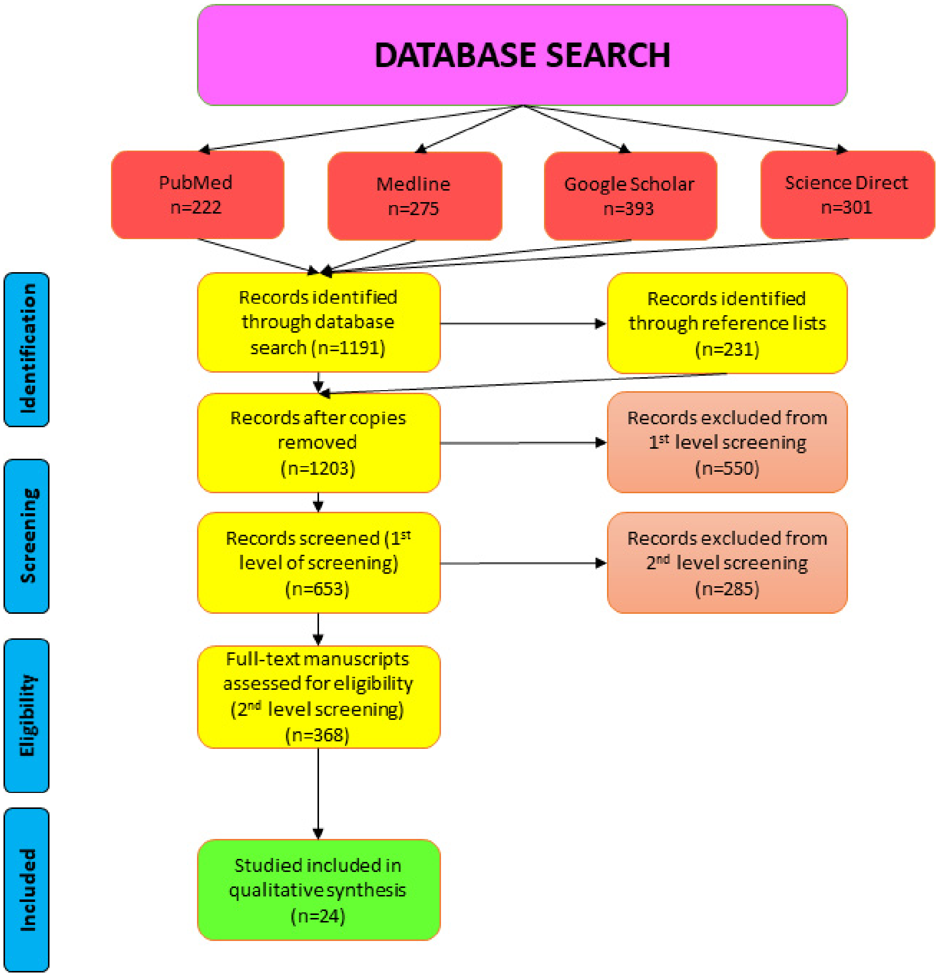


Fig. 1. Flow diagram of the search strategy.

At the second level of screening, from the 653 selected studies that passed the first screening stage, 285 papers were excluded for the same reason, therefore 368 papers proceeded for the second level screening. The related publications were assessed for overlapping and unique information relevant to this analysis. After a full review of the text, finally, 24 papers used for analysis and discussion, as shown in Fig. 1.

3.2. *Study characteristics-risk of bias of the included studies – biomechanical factors*

In this systematic review, we included 10 studies that assess THA biomechanics and wear responses to load, 11 studies that investigate THA wear after *in vitro* testing of biomechanical factors (kinematic or/kinetic) and three studies that examine wear of

Table 2. Data items included at the systematic review. The table presents the examined wear factor addressed from each study, the research team and the year of publication.

Wear assessment factor	Research Team-Journal-Year	Number of hips	Intervention	Time frames
In vivo THA biomechanics and wear	Foucher *et al. Clin Biomech* 2008	15	primary	12 months
	Foucher *et al. J Orthop Res* 2009	48	primary	12 months
	Ardestani *et al. Clinical Orthopaedics and Related Research* 2017	73	primary	12 months
	Asayama *et al. J Arthroplasty* 2005	30	primary	18 months
	McGrory *et al. J Bone Joint Surg Br* 1995	86	70 primary-16 rev.	12 months
	Matsushita *et al. J Arthroplasty* 2009	11	N/A	N/A
	Devane *et al. Clin Orthop Relat Res* 1999	82	primary	5, 5 years
	Barrack *et al. Orthopedics* 1998	25	N/A	N/A
	Sakalkale *et al. Clin Orthop Relat Res* 2001	34	primary	5, 7 years
	Bjørdal *et al. J Orthopaed Traumatol* 2015	148	N/A	12months
THA wear after *in vitro* testing of biomechanical factors	Hadley *et al. Proc Inst Mech Eng H.* 2018			
	Keurentjes *et al. Clin Orthop Relat Res* 2008			
	Hannouche *et al. Clin Orthop Rel at Res* 2003			
	Willmann G. *Clin Orthop Relat Res* 2000			
	Walter *et al. J Arthroplasty* 2007			
	Jörn Reinders *et al. PLoS One* 2013			
	Affatato *et al. Biomaterials* 2001			
	Yu-Lei Dong *et al. Chin Med J (Engl)* 2015			
	Amanatullah *et al. J Arthroplasty* 2011			
	Kim *et al. Int Orthop* 2013			
	Lewis G. *Biomaterials* 2001			
Wear for CoC or/and CoXLPE THAs through clinical factors	Amanatullah *et al. J Arthroplasty* 2011	357	Primary	5 years
	Hu *et al. Orthopedics* 2015	1747	Primary	1–8 years
	Si *et al. Hip Int* 2015	2488	Primary	2–12, 4 years

CoC or/and CoXLPE THAs through general factors (radiographic, clinical). The results of this study proceeded for narrative synthesis.

Table 2 presents the studies indicated in the discussion and implications segment. These studies accurately assessed the criteria set at the methodology with a low risk of bias for clinical factors and high evidential value for biomechanical factors.

4. Discusssion

When evaluating wear testing in THAs, both joint kinematics and joint kinetics are considered as essential input parameters. According to International Organization for Standardization (ISO), there are specific references about comparative angular displacement between the various components, the applied force characteristics, the speed and duration of testing, the sample configuration, and the test environment to be used when testing total hip-joint prostheses for wear (ISO 14242-1:2014).[20] That emphasizes the role of joint kinematics and kinetics as parameters of wear. The purpose of this study is to review the effect of kinematics and kinetics on wear (*in vivo* and *in vitro* testing) that affect wear in Ceramic on Ceramic and Ceramic on

XLPE total hip arthroplasties and identify possible advantages amongst them. This systematic review of the literature does not provide sufficient evidence of kinematic or kinetic advantage for any of the examined implant designs in terms of wear. These findings could be used for further research by biomechanists in order to improve THA implants' wear behavior, which could lead in improved wear rates. The provided information could also help orthopedic surgeons with their decision making when the wear rate is the key factor of interest.

THA wear is attributed to factors such as implant design variables (geometric features and material properties),[21–27] variables during surgery (implantation method and component positioning),[28,29] and patient factors.[30–32] In the last category, the hip contact force, a variable determined by gait and motion patterns, significantly contributes to polyethylene wear.[33,34]

Gait is humans' most essential functional activity where THAs subject to loading. A research from Ardestani *et al.* tried to investigate the comparative influence of gait and surgical positioning on wear. According to their predictive models (a multiple linear regression MLR and an artificial neural network ANN), gait parameters explained 42–60% of wear rate, while surgical factors such as components' positioning explained 10–33% of the wear rate on traditional Metal on Polyethylene bearings.[35]

Several studies evidently showed the significance of offset in the clinical result after a THA. More specifically, an increase in offset results in an increased range of motion, better mechanical advantage of the abductors, and increased stability due to increased soft tissue tension.[36–38] Unrestored preoperative hip biomechanics through femoral component's offset can increase joint reactive force and moments, hence increasing polyethylene wear.[39–42] Since THA kinematics (ROMs) and kinetics (moments) during gait are important biomechanical parameters directly associated to wear of the implants as mentioned above and the results in our study do not demonstrate a statistically significant difference in moments or ROMs between the two groups, we conclude that none of the two implants has a comparative advantage over the other regarding the biomechanical loading.

A common technique that implant industry uses to test and evaluate wear performance of THA components before clinical trials is hip simulator. Apart from only replicating kinematics and kinetics of walking patterns, modern simulation techniques try to include more adverse daily activities to improve the accuracy of wear predictions.

In their study, Hadley *et al.*[43] examined wear performance of CoC, MoP, and CoP in two stop-dwell-start protocols, one average and a second more severe. All materials produced increased wear rates under adverse stop-dwell-start conditions compared to normal, with CoC showing the least wear among materials in every test performed. The authors attributed that behavior to the depletion of lubricant in the bearing during the dwell period. Different lubrication mechanisms in each bearing type might explain the discrepancies among the models examined. However, breakage (rare incidence of 0–2% depending on the ceramics used[44–46] and squeaking (incidence 0.5–20.9%[44–48] of ceramic components are still a concern. Wear rates and osteolytic potential of CoC bearings have been shown to be lower than those of CoP bearings in laboratory experiments in other studies too.[13,49]

Yu-Lei Dong *et al.* in Ref. 49 a recent meta-analysis of eight prospective randomized trials that enrolled a total of 1508 patients and 1702 THA surgeries, highlighted the lower wear rate of CoC bearings, but overall the lack of sufficient evidence to identify any significant clinical advantage of CoC compared to CoP. Amanatullah *et al.*[50] compared CoC versus CoP at a follow-up of five years. In the ceramic–ceramic group, the mean linear wear rate was $30.5 \pm 7.0\,\mu$m/year, and the mean volumetric wear rate was $21.5 \pm 4.5\,\text{mm}^3$/year. In the ceramic-PE group, the mean linear wear rate was $218.2 \pm 13.7\,\mu$m/year, and the mean volumetric wear rate was $136.2 \pm 8.5\,\text{mm}^3$/year. The increase in mean linear and volumetric wear rates in the ceramic-PE group was statistically significant ($P < 0.001$). Kim *et al.*[51] compared CoC versus CoXLPE for an average of 12.4 years. The mean total amount of highly cross-linked PE linear penetration was 0.337 ± 0.315 mm, and the mean annual penetration rate was 0.031 ± 0.004 mm/year, while the COC wasn't detectable. Lewis *et al.*[52] compared CoC and ceramic on ultrahigh-molecular-weight PE liner, reporting a statistically significant difference in total wear between the two bearing groups ($P < 0.001$). The annual wear rate found 0.02 mm for the CoC group compared to 0.11 mm/year for the CoP group. All three studies favor the CoC and demonstrate significantly lower wear rates.

All the above-mentioned studies agree that CoC bearings show a lower wear rate compared to CoP when tested under the same biomechanical conditions *in vitro*. This study demonstrates the same biomechanical behavior for both implant types during gait too.

A metanalysis[53] found no significant clinical and radiographic differences between CoC and CoP bearings with respect to revision, osteolysis, and radiolucent lines, loosening, dislocation, and deep infection. There was no sufficient evidence to support any clinical or radiographic advantage of CoC versus CoP bearing surfaces in the short- to mid-term follow-up period. The authors suggested that long-term follow-up is required for further evaluation. Dong *et al.* reached in the exact same conclusion in their meta-analysis of CoC compared with CoP, proposing longer monitoring of more extensive randomized trials to clarify the outcomes.[49]

In line with the previous researches, Si *et al.*, in their systematic review and meta-analysis, concluded that no clear evidence favors the use of either a CoC or CoP bearing surfaces in primary THA. They proposed further studies with high-quality and longer-term follow-up to provide more evidence on this topic.[54]

5. Conclusions

THA is an effective treatment for severe hip arthritis, with patients reporting high rates of satisfactory results postoperatively. There is a variety of choices regarding THA implant designs. Ceramic on ceramic and ceramic on XLPE THAs are the materials of choice nowadays. There is no significant evidence for biomechanical advantages between these two that could affect wear and, therefore, longevity. Further research is proposed with the use of gait analysis systems combined with surface electromyography[55,56] to deeper investigate THA biomechanics at a laboratory set up. Wearable sensors technology could also identify detailed biomechanical parameters in more complex daily activities.[57]

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