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Review

Fretting Wear and Corrosion-Related Risk Factors in Total Hip Replacement: A Literature Review on Implant Retrieval Studies and National Joint Replacement Registry Reports

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Abstract: Fretting corrosion is a known failure mechanism of total hip replacement (THR) that can lead to revision surgery. Implant retrieval studies have thoroughly documented the occurrence of fretting corrosion in THR implants and its correlation with implant- and patient-related factors. Although implant retrieval studies benefit both clinicians and implant manufacturers, the limitations of these types of studies need to be acknowledged. For example, while some factors are routinely investigated for a possible correlation with failure due to fretting corrosion, other factors are often assumed to have no effect. To improve on these limitations, this review investigates the most significant patient- and implant-related risk factors for fretting corrosion of THR implants for both published retrieval studies and joint replacement registries. The findings and limitations are discussed critically. It is concluded that retrieval studies add significant insight into implant failure mechanisms and should be used in conjunction with joint replacement registry reports. It is suggested that the development of reliable predictive models based on implant failure risk factors and decision-making support systems could lead to enhanced implant longevity.

Keywords: total hip replacement; implant retrieval; fretting corrosion; big data; joint registry

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1. Introduction

Total hip replacement (THR) is the treatment for end-stage hip osteoarthritis [1–4]. Although recent data show that the outcomes of THR have improved over time, a minority of patients continues to have suboptimal results [5], some of which are related to implant failures [6]. Implant retrieval studies are used to determine the cause of revision THR related to implant failures. Fretting corrosion, a complex mechanical wear and corrosion phenomenon occurring at the interface between modular components (e.g., head-neck taper junction) due to the cyclic relative micromotions and corrosive environment present around the joint, is one of the best-documented reasons for implant failure [7–14]. Most retrieval studies specify the impact of different variables on failed implants using methods that identify the severity of fretting corrosion on the surface of prostheses [15]. However, based on the reports of several joint replacement registries, fretting corrosion does not seem to be an important factor for THR revisions, perhaps due to the reporting methods. Surgeons are being asked what they think is the primary cause of revision THA, rather than noting what factors may have contributed to revision. Fretting corrosion is recognized as a cause for revision independent of other modes of failure and plays an important and sometimes even fundamental role in other THR complications. For example, corrosion products and debris particles can cause osteolysis and loosening, both common causes of long-term THR failure and revision [16,17]. Given the improvements in polyethylene wear, fretting corrosion may now be one of the principal causes for osteolysis and loosening in the long term (defined as >10 years) [18]. This important matter has been raised by authors of recent retrieval studies reporting on the severity of fretting corrosion damage of the surface of retrieved implants [11,12,19]. At the same time, retrieval studies can only provide information about the cohort of implants and patients at hand, with limited additional information available. As a result, only few factors on a limited number of implants are investigated for possible correlation with failure, while other factors are assumed to have no effect or are ignored. Moreover, the common scoring methods are quite subjective. This may explain why the findings of different retrieval studies do not concur and sometimes contradict each other [20].

A good implant retrieval study requires a multilevel strategy to address a wide range of relevant variables. This includes analyzing patient and implant data separately, and then analyzing their interactions. The key question to ask is how the findings of implant retrieval studies can be used in the clinical decision-making process of implant selection to improve implant survivorship while taking into consideration a number of patient characteristics. Joint replacement registries may be able to address some of these issues given their ability to analyze big data.

This paper aims to review the existing literature related to THR implant retrieval and recent reports of joint replacement registries to identify the most significant risk factors for revision THR. We also discuss correlations between reported outcomes and the limitations of these studies to better identify their weaknesses.

It is noted that a few other review papers on this topic have been published previously [20–22]. However, it is important to recognize that fretting corrosion is a dynamic topic of interest that generates new findings every year. This necessitates frequent review to help understand the factors that can significantly impact THR outcomes. This work includes data from both retrieval studies and registry reports.

2. Implant Retrieval Studies

Implant retrieval studies help to enhance our knowledge of length of implantation (LOI) as a major outcome parameter. A common method for measuring the severity of fretting corrosion is based on the visual scoring of damage on the surface of the implant (taper junction), which was introduced by Goldberg et al. in 2002 [15].

Figure 1 shows the four-level scoring method based on predefined visual parameters. These include the shape, colour, and reflectivity of the damaged areas where 1 shows no damage, 2 is mild, 3 is moderate, and 4 indicates severe corrosion damage [15]. As of today, this scoring method or modified versions have been used in many hip implant retrieval studies [12,23–26]. For instance, the modified scale of Goldberg includes an extra score between "no visible" and "mild levels of corrosion damage". This was used in a retrieval study for grading the process of corrosion at mating surfaces: no corrosion = 0; minimal corrosion = 1; mild corrosion = 2; moderate corrosion = 3; and extensive corrosion = 4 [27]. In addition, the incidence of corrosion has been recently investigated using image processing methods in order to standardize the scoring process of implants [28–30].

There are different factors that can affect the outcome of THR, including patient characteristics [31–34]. However, authors are usually limited by the lack of patient information associated with retrieved implants. In the next section, several published retrieval studies with available patient data will be reviewed with a focus on identifying important patient characteristics. It should be noted that distinguishing patient-related variables from implant-related factors is not trivial. Most studies have only investigated the effects of implant characteristics on the severity of fretting corrosion without considering patient-related factors.

Figure 1. An example of the fretting corrosion damage scoring of the trunnion [29].

2.1. Patient Data in Retrieval Studies

There are many challenges around accessing patient data and failed implant reports. Some research studies have focused on only a small number of patient or implant variables because of these existing barriers. In many studies, age and gender have been included to categorize retrieved hip implants [35–37]. For instance, the effect of taper design on the fretting corrosion of the head-trunnion surface was studied using retrieved prostheses with the same LOI [35]. Taper groups had no differences in age ($p = 0.34$) and body mass index (BMI) ($p = 0.29$). Gender and time in vivo were also considered as the other patient characteristics in this work (Table 1). The Goldberg scale was used by two independent observers for scoring fretting and corrosion in three zones (apex, central, and base), as shown in Figure 2. The 11/13 taper showed the highest fretting and corrosion scores among all groups (DePuy 11/13 (Warsaw, IN, USA), Smith and Nephew 12/14 (Memphis, TN, USA), Zimmer 12/14 (Warsaw, IN, USA), Depuy 14/16, Stryker 5°38′37″ (Kalamazoo, MI, USA), and Stryker 2°52′). The highest corrosion score was recorded at the base zone in a zone-specific analysis.

Table 1. An example of patient data and reason for revision in a study population [35].

Demographics	Mean
Age at revision (years)	69.4 (±13.5)
BMI (kg/m^2)	29.6 (±7.3)
Gender (male:female)	20:24
Time in vivo (years)	8.9 (±3.7)
Reason for revision	**Number**
Aseptic loosening	19
Polyethylene wear	8
Periprosthetic fracture	7
Instability	2
Infection	4
Implant malposition	1
Others	3

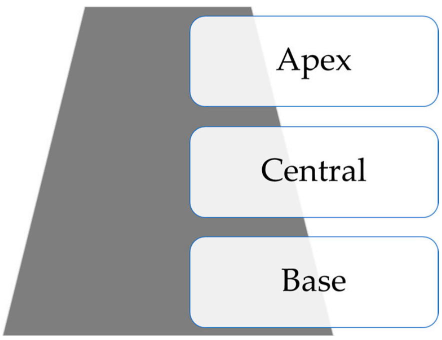

Figure 2. Diagrammatic representation of three concentric zones of the femoral head bore and stem tapers; figure reproduced from [38].

Tan et al. [39] investigated the effect of implantation time, gender, age, and BMI (Table 2) on fretting and corrosion. Retrieved prostheses with a total of 52 ceramic heads from different manufacturers were selected. These were matched to a cobalt–chromium (CoCr) cohort, according to the neck length, taper design, implantation time, and head size. A four-point scoring system was used in three zones (base, middle, and apex) by two observers. Implantation time and taper design were reported as the most significant factors affecting the severity of fretting corrosion. Taper design had the most significant correlation with the rate of fretting corrosion in the apex zone ($p = 0.04$). Implantation time was also linked to a worse fretting corrosion score in the CoCr cohort when compared to the ceramic cohort. There are other patient-related metrics that can be assessed to identify fretting corrosion in THR revisions. A clinical-based paper in 2016 [40] reported that a combination of patient symptomatology, laboratory values, and imaging findings are required for any decision in performing revision surgery. Patient symptoms and metal ion levels were taken into account to assess the presence of an adverse local tissue reaction (ALTR). This shows the importance of considering individual patient clinical information along with implant-related factors.

Table 2. Demographics of the CoCr and ceramic cohorts [39].

Demographics	Ceramic (Mean)	Cobalt–Chromium (Mean)	*p* Value
Age (year)	57	66	0.001
Male:Female	28:24	33:19	0.32
BMI (kg/m^2)	23.4	29.7	0.15
Implantation time (year)	8.6	8.4	0.83

In an investigation on patient-related and prosthesis-related factors [26], it was found that body weight, flexural rigidity, and stem material are significant variables affecting the severity of fretting and corrosion scores in a cohort of patients with ceramic heads. Both in vivo and in vitro studies have shown similar results previously [15,41–44]. However, gender, head size, and lateral offset were not reported as significant predictors of corrosion, which is similar to what Carlson et al. found in another study [41]. These results did not agree with prior work by Goldberg et al. [15], where lateral offset was found to be a cause of severe corrosion. An association between femoral head size and corrosion was verified in another retrieval study [45] in which one hundred femoral head-stem pairs were used for analyzing corrosion and fretting with visual scoring. The heterogeneity of the results found in numerous retrieval studies highlights the need for using large-scale data in further studies. This would help to: (a) identify the effect of different variables on the fretting and corrosion scores of retrieved implants and (b) create predictive models based on these variables.

A study on Co and Cr ion levels in the blood before revision THR showed that CoCr-cemented stems are prone to severe corrosion [46]. It is important to note that the stem–cement interface is the main source of releasing metal ions into the body, even if the trunnion remains undamaged. At the stem–cement interface, this study highlighted that fretting corrosion can significantly contribute to high levels of metal ions causing extensive soft tissue necrosis with the associated tribo-corrosion and tribo-chemical mechanisms. The patient data used in this study were the same as the previously reviewed paper with the addition of cup inclination as an implant characteristic. After analysing 36 cemented stems consisting of CoCr and stainless steel in a series of MoM hips, it was reported that CoCr stems are the largest potential source of metal ions and that using cemented femoral stems increases the probability of severe corrosion. High concentrations of cobalt and chromium in the blood were also reported as a harmful effect of fretting corrosion [47]. This is in addition to other effects of corrosion such as metal ions and particles at modular taper junctions [48–53], which have been reported as a link to hypersensitivity, lymphatic reactivity, chromosomal damage, local tissue toxicity, malignant transformation, and impaired renal function [54,55]. As a result, more active patients may be prone to more severe corrosion at modular junctions. Fretting and the increased cyclic loading of the interfaces result in creating an environment conducive to corrosion. This finding raises a significant concern for the performance of modular implants in active patients in the long term [56–61].

Overall, the literature indicates that age and the American Society of Anesthesiologists (ASA) score are proxies for the patients' level of activity and that, in addition to gender and BMI, should be selected as the main non-image-based patient data that influence the outcome of THR (Table 3). The authors believe that increased blood metal ion levels may not be necessarily used as a biomarker for the severity of corrosion. This is because there may be issues regarding the reported results, such as the timing of metal ion measurements in relation to revision surgery and proving the origin of corrosion, which is in fact from modular junctions and not bearing surfaces.

Table 3. Patient-related risk factors for fretting corrosion.

	Risk Factor/Potential Predictor
1	Age
2	Gender
3	BMI
4	ASA score

2.2. Implant Data in Retrieval Studies

In this section, the effect of implant-related characteristics on the severity of fretting corrosion is reviewed. The selected papers are divided into three parts (design, material, and manufacturing) based on the implant-related variables that were assessed in the retrieval studies.

2.2.1. Implant Design

In two similar retrieval studies [38,62], the effect of femoral head size on the severity of fretting corrosion was investigated in retrieved head-neck tapers. All of the selected Metal-on-Polyethylene (MoP) implants were in vivo for at least two years. Seventeen femoral stems with a single taper design (eight Synergy, seven Spectron, and two Echelon from Smith & Nephew) and 56 of 28 mm heads (neck lengths ranging from −3 mm to +8 mm) articulating with a polyethylene liner were involved in these studies. Three horizontally oriented zones were considered for scoring the fretting and corrosion of each taper. The results showed a greater total fretting score for the longest neck length (+8 mm) compared with all others ($p = 0.03$). Increased fretting damage ($p = 0.01$) was also identified most in the central zone of the femoral head bore, regardless of the stem offset or neck length. High-offset femoral stems were associated with greater taper fretting ($p = 0.04$). As a result, higher fretting damage was observed in the high-offset femoral stems and longer neck lengths. Subjective scoring measures and a small range of implant sizes are the significant limitations of these two studies [38,62]. In these papers, only the 12/14 mm taper design by Smith & Nephew was studied, even though more than 30 types of head-neck tapers are commercially available [63]. Some patient information including age, gender, implant side, BMI, and reason for revision were obtained from the medical records. No accompanying differences were noted in the taper corrosion scores, while others previously reported that the distal part of the taper (i.e., base) showed more corrosion than the proximal part (i.e., apex) (Figure 2). It was also suggested that the apex region is the most susceptible to corrosion because of fluid ingress, mechanical loading, and the effects of crevice geometry at this location.

The outcomes of several studies suggest that large head sizes are associated with increased severity of corrosion at the head-neck taper; for example, larger heads (i.e., 36 mm) produce more corrosion than smaller heads (i.e., 28 mm) [38]. However, no relation between head size and fretting or corrosion scores was previously reported by Goldberg et al. [15] in a multicentre retrieval study. These inconsistencies were explained by the fact that taper designs with a various range of head sizes from several manufacturers were studied. This may mean that other factors such as the manufacturing processes may play a role in the outcomes of retrieval studies. As previously mentioned, differences in the results of various studies can often be justified by exploring their limitations. For example, evidence of fretting could be masked from the observer in cases with extensive corrosion debris. Moreover, portions of the implants may also be inaccessible for observers to inspect properly because of the geometry of the taper. The small number of implants assessed also proves to be a barrier for detecting important outcomes related to the study of large cohorts of implants.

The use of additional modularity at the stem-neck junction, which has become more common over the last 25 years, simplifies adjustments of offset, femoral neck version, and leg length [64,65]. That said, the initial designs of this increased modularity made of titanium alloy showed poor performance against fracture risk because of unsuitable fatigue strength [64,66]. To resolve this issue, cobalt chromium alloy was used in the manufacturing process to improve implant stiffness. A significant decline in the risk of fracture of dual-taper modular components was achieved after this change, although the fretting corrosion of mixed-alloy neck-stem junctions has increased due to increased micromotion [49,58,67]. This generation of corrosion debris at the neck-stem junction seems to be the culprit for ALTR in many patients with dual-taper femoral components [68–71], which is a distinctly different entity from the generation of wear debris and corrosion of the bearing surfaces.

In a retrieval study [7] of 60 dual-modular implants (Rejuvenate, Stryker) from 55 patients (20 men and 35 women) with an age range of 45–79 years revised for ALTR, evidence of fretting corrosion was observed at the neck-stem taper in all implants. However, fretting corrosion was not seen on all of the head-neck tapers. Severe fretting corrosion damage at the neck-stem taper was also reported in work by Molloy et al. [72]. Their outcomes show that the poor long-term performance of neck-stem modular junctions may be more detrimental than head-neck taper junctions. Furthermore, the use of a specific beta titanium alloy in the setting of neck-stem taper or the specific design (ABG II, Stryker) of the modular taper was suggested as the main cause of failure [7]. This illustrates the importance of identifying and evaluating different variables simultaneously (e.g., design and material combinations, etc.) to help clarify and understand failure causes.

Some retrieval studies of dual-taper implants have found a correlation between the severity of fretting corrosion and other parameters such as stem size, neck-shaft angle, and neck length. Higher corrosion scores are reported in femoral stems paired with long neck lengths due to cyclic cantilever bending at the neck-stem junction in vivo. In one retrieval study [7], three implants were graded in eight independent zones. These included the proximal and distal aspects of the neck tapers, further divided into medial, lateral, anterior, and posterior regions (Figure 3). A clear pattern of increased fretting corrosion in two retrieval studies [7,40] with similar mean corrosion scores in different zones suggested the occurrence of cyclic cantilever bending at the neck-stem junction in vivo. Micromotion occurs with each step of the gait cycle. The magnitude of this bending moment increases with increasing the distance from the load axis to the taper junction. Table 4 shows the mean fretting and corrosion scores for different zones found in one study [7]. In this paper, a positive correlation between longer neck lengths (34/38 mm) and increased severity of corrosion (not fretting) on the femoral stem was reported. No correlation was found between the stem size or neck-shaft angle and fretting or corrosion of the femoral stem or modular neck. It was also suggested that variables such as the patient's history, physical examination, laboratory studies, and imaging including plain radiographs and metal artifact reduction sequence (MARS) MRI should be considered for further retrieval analyses. This is further supported by the official recall statement issued by Stryker [73] and the algorithms for treatment of patients with a modular THR shown by Kwon et al. [74] and Pivec et al. [75]. Evidence of fretting and corrosion was reported by Kop and Swarts [58] in 6 of 16 retrieved modular hip implants (double-tapered and cone-shaped) at the neck-stem taper, with only three implants showing corrosion at the head-neck taper. The neck-stem junction showed a greater propensity for micromotion because of an increased lever arm compared to that of the head-neck junction. Similar outcomes with evidence of corrosion at the neck-stem taper and minimal damage at the head-neck taper were also reported by Gill et al. [69].

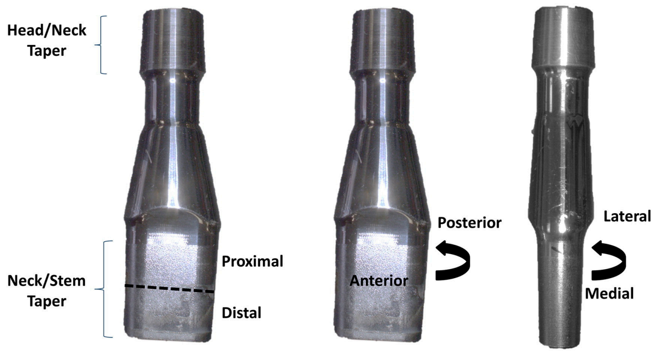

Figure 3. Regions of interest of the modular neck [7].

Table 4. Average fretting and corrosion scores of femoral stem and neck surfaces [7].

Damage Mode	Region of Interest Medial	Anterior	Lateral	Posterior
Fretting (stem)	1.1 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	1.1 ± 0.1
Corrosion (stem)	4.0 ± 0.04	3.8 ± 0.1	3.9 ± 0.1	3.9 ± 0.1
Fretting-proximal (neck)	1.8 ± 0.1	1.1 ± 0.04	1.5 ± 0.1	1.6 ± 0.1
Fretting-distal (neck)	2.2 ± 0.1	1.4 ± 0.1	1.8 ± 0.1	1.9 ± 0.1
Corrosion-proximal (neck)	3.5 ± 0.1	1.8 ± 0.1	2.7 ± 0.1	3.0 ± 0.1
Corrosion-distal (neck)	3.7 ± 0.1	3.2 ± 0.1	3.6 ± 0.1	3.5 ± 0.1

Some studies document corrosion of modular-body hip implants in a large series of single design components [56,57,76]. In a study on the S-ROM stem (DePuy) [41], the fretting and corrosion of 78 modular cementless titanium-alloy hip implants with a single design were evaluated. Since the introduction of the S-ROM stem in 1984, a variety of proximal body heights and offsets, stem lengths and diameters, calcar spout sizes, and proximal sleeve diameters have been used as a useful tool to manage complex primary THA. In this study [41], seven implants with a femoral stem fracture were assessed separately to identify the reason for failure. The type of material (metal and ceramic) and the use of similar versus dissimilar alloys for the key components of stem-sleeve and head-neck junctions were found to play a major role in the severity of damage. This will be discussed in more detail in the next section which focuses on materials. This study [36] also found that in vivo duration was not an acceptable predictor of corrosion at the head-neck interface, but it was a significant factor of predicting stem-sleeve corrosion.

Not all studies reviewed share agreement on the cause of corrosion. The presence of blood, tissue, and organic fluids in the environment of sleeve engagement was introduced as the main cause of severe corrosion at the stem-sleeve taper in one group of studies [60]. Other retrieval studies with similar outcomes noted that increased corrosion at the stem-sleeve interface is because of fluid acting as a conduit for ion exchange within the taper, which may be present from the first few cycles of motion [76,77]. Another study demonstrated that the presence of fluid in a taper junction at the time of implantation may act as a barrier for achieving a friction fit between the two modular components, thereby increasing the probability of severe fretting corrosion under in vivo loads [8].

Overall, while the use of modular devices in THR is advantageous for both implant manufacturers and surgeons, the negative effects of fretting corrosion will likely remain a problem moving forward. However, there is room for significant improvement by considering patient factors, implant design, and surgical technique. Coupled with this, reporting of large-scale retrieval studies needs more attention given the complex interplay of multiple variables on fretting and corrosion.

2.2.2. Materials Used for THR Implants

By convention, the bearing surface of a THR is named after the material of the femoral head component, followed by the material of the acetabular liner. Metal-on-polyethylene (MoP) bearings are the most common combination of materials in THR [78]. In general, the greatest disadvantage of MoP bearings is the release of polyethylene wear debris. However, reductions in the release of particulate debris and also wear rates were achieved with the creation of highly cross-linked polyethylene (HXLPE) [79–81]. Polyethylene has been shown to be a cost-effective liner option with a predictable lifespan [78,82,83]. MoM has gone out of favour and are no longer commonly used by surgeons. Large diameter MoM bearings with poor design, metallurgy, or fixation showed early failure [84–87]. Greater exposure to metallosis and the potential of carcinogen exposure from MoM bearings were reported as significant drawbacks from their use in numerous studies [88–90]. The use of ceramic in ceramic-on-ceramic (CoC) bearings has the benefits of causing minimal tissue reaction, exhibiting low friction properties, and minimal generation of debris particles. The downsides of ceramic are its cost, the potential of squeaking in situ, and its requirement of careful insertion to prevent catastrophic ceramic fracture [91–93]. A low wear rate has been reported with the use of ceramic bearings, although their brittle nature is a concern for revision in case of fracture [94,95]. Two studies on CoC THR have demonstrated that noise from squeaking, rubbing, grinding, and other audible sounds from the hip occur most frequently (in 10–17%) in patients with CoC bearing surfaces [96,97].

Collier et al. [98] verified that duration-dependent evidence of crevice corrosion was seen in over half of retrieved mixed-alloy modular junctions while all similar alloy components did not show any sign of crevice corrosion. They showed that metal heads cause more severe corrosion at the head-neck taper when compared to ceramic heads. After investigating the effect of head material on the severity of fretting corrosion at head-neck tapers, Hallab and his colleagues found higher fretting in metal–metal than ceramic–metal head-neck junctions [99].

Referring back to reference [36], the authors analyzed the stem-sleeve junction with similar alloys and the head-neck junction with dissimilar alloys. They found that damage at both the stem-sleeve junction (65% fretting; 88% corrosion) and the head-neck junction (88% fretting; 54% corrosion) was substantial. It was stated that corrosion was correlated with metal (vs. ceramic) femoral heads, patient activity, and time since implantation, but was not correlated to the head carbon content. No statistical difference in corrosion was found by categorizing metal femoral heads into high and low carbon concentrations.

Improvements in material combinations, material composition/metallurgical state, and metal–metal interfaces may optimize the performance of implants in the future.

2.2.3. Implant Manufacturers

There are several companies that manufacture hip replacement implants. These companies use a variety of materials with different plastic, metal, and ceramic combinations to cover a wide range of indications for the needs of specific patients [100,101]. There are few retrieval studies and references to assess the role of manufacturers in the results of THR. The general lack of information and the complexity of the interplay between numerous variables were noted as the reasons for this [102,103].

In THR, surgeons often use various brands of implants. This is in part related to certain manufacturers not producing a full spectrum of implants. For instance, for a particular period of time, Midlands Medical Technology (Birmingham, UK) only manufactured a modular head, without an accompanying femoral stem [104,105]. The National Joint Registry (NJR) noted that many registered mixed manufacturer (MM) components had been used in upwards of 15% of cases [106]. Manufacturers test the head and trunnion to make sure they are compatible and suitable for clinical purposes. However, they highly recommend that components should not be MM because of slight differences in the surface size, and also variations in manufacturing processes and materials [107].

As mentioned above, the pairing of MM components is common. From a legal perspective, there are studies that suggest mixing components are not advised when other reasonable choices are available [108]. A potential exists for poorly fitting components which increases the risk of failure due to the increased rate of wear [102,109,110]. A finite element study reported that small variations of the trunnion angle may cause a significant difference in the magnitude of micromotions [111]. DePuy, a well-known manufacturer, has also stated that the tolerance of their trunnions can affect outcomes [112]. Despite this, other registry-based research and clinical studies have found that the failure rate of MM may not be greater than SM [106,113,114], which is in line with the findings from Whittaker et al. [115]. To complicate the matter, another study found that the influence of these tolerances on wear rates is associated with the differences in the surface finish of the components [116].

One study [115] compared the rate of wear and corrosion at the head-neck taper junction in two groups of retrieved hip implants: same manufacturer (SM) and MM sets. A total number of 151 large-diameter CoCr retrieved hip implants were studied. These included 100 sets with seven different head designs paired with stems from the SM and 51 sets of two different head designs paired with stems from MM. No significant difference was found in the material loss and corrosion scores of the two groups. This implies that pairing stems with heads from different manufacturers does not have any negative impact on the implant's fretting corrosion levels. It is noteworthy that head designs from two different manufacturers (Birmingham Hip Resurfacing (Midland Medical Technologies, Birmingham, UK) and Adept (Finsbury, Leatherhead, UK)), and stem models of different companies (CPT, CLS and Alloclassic from Zimmer; Synergy and CPCS from Smith and Nephew; CBH and Twinsys from Mathys; Corail from DePuy; Lubinus MP Reconstruction Prosthesis from Link; Freeman from Finsbury; MS-30 from Sulzer; Furlong from JRI; Taperloc from Biomet; and Metha from Aesculap) were included in this study. Trying to assess materials in manufacturer-specific implants in the analysis of fretting and corrosion is unlikely to be fruitful. The manufacturing of THR components is a massive global industry, and the legal implications of intellectual property and patents make obtaining data for advanced analyses and materials difficult.

A review of the three aspects (design, material, and manufacturing) of implant-related variables (Table 5) showed that head size is the main parameter contributing to severe tribocorrosion damage at the taper junction in the most commonly used implants [24]. Material properties and bearing surfaces should be noted as the second most significant group of factors. Metallurgical state, microstructures, and the carbide distribution of implants may also be associated with fretting corrosion [117,118].

Table 5. Implant-related risk factors for fretting corrosion.

	Risk Factor/Potential Predictor
1	Head size
2	Modularity
3	Fixation method (Cemented/Cementless/Hybrid)
4	Materials combination
5	Material composition and metallurgical state
6	Flexural rigidity of the neck
7	Surface finish
8	Taper geometry and tolerances
9	Presence of multiple metal–metal interfaces
10	Stem design
11	Bearing design

3. Risk Factors from a Joint Registries (JRs) Perspective

As noted previously, implant retrieval studies have been used predominantly to examine modes of failure in THR. However, the field of retrieval analysis suffers from the lack of consistent information on surgical operations because there is no means of tracking the number of implantations or failures of devices until problems arise. Many issues with implants are related to the method of implantation or the surrounding biologic environment of each specific patient, rather than the device itself. A traditional hypothesis-driven study with high statistical power is often not a practical approach in these cases. It is not necessarily an effective tool to compare implants due to the presence of many prosthesis- and patient-related factors at play. A good implant retrieval study requires a multilevel strategy to address all relevant variables. This includes analyzing patient and implant data separately and in combination, as each can have a substantial role in the failure of an implant.

In orthopaedics, JRs record data on joint replacements to closely observe their effectiveness [119]. These registries can identify issues with implants and surgical methods through statistical analyses [120–122]. This is especially important in the field of joint replacement, which has consistently had to aim to enhance the longevity of medical implants and minimize failure and revision rates for patients. For this purpose, significant collaborations at an international level should be developed between various research groups and registries. As a clinical subject, big data has been recently used in healthcare applications for developing predictive models and clinical decision support systems, as well as for predicting disease and safety surveillance [4,123–128].

The incidence of fretting and corrosion is likely largely underestimated in registry reports. Corrosion products and debris particles may cause pain [129], infection [130,131], and the aseptic loosening of implants [132–136]. One suggestion to improve this underestimation would be to request specific information about the intraoperative evidence of fretting and corrosion from surgeons when completing registry forms. Given the substantial role of joint replacement registries in monitoring arthroplasty outcomes, this would give us a much better idea of the true incidence of fretting and corrosion in revision total joint arthroplasty.

Patient factors that affect the result of THR are being gathered by the AOANJRR [6,137,138]. ASA score and BMI have been collected since 2012 and 2015, respectively. No differences were reported in revision rates of the underweight or pre-obese patient groups. Revision rates increased for the obese class 1, obese class 2, and obese class 3 groups. It is also noted that the rate of revision changes with patient characteristics and the follow-up time. For example, patients aged 75 years or older have a lower rate of revision than those aged <55 years after 3 months, between 55 and 64 after 6 months, and 65–74 years after 4 years. Gender is another factor that plays a role in revision rates as they were found to decline for females with increasing age [6]. These findings corroborate those of prior retrieval studies, further underlining the importance of analyzing the two together.

The American Academy of Orthopaedic Surgeons (AAOS) states that metal ion levels are influenced by confounding factors such as implant materials, type, design, positioning of implant, and diameter of bearings [139]. From a clinical perspective, the AAOS also suggests that while metal ion level is a useful parameter for assessing MoM hip arthroplasty, there are limitations in terms of its role for clinical assessment purposes. As such, metal ion levels cannot be solely relied on as a significant parameter to conclude clinical recommendations as there is confounding in the interpretation of metal ion levels in patients with bilateral MoM total hip. Data from a randomized clinical trial showed no indication of severe trunnion corrosion in the head-neck taper with low metal ion levels in blood (medians < 0.3 μg/L) [140]. Høl et al. also found no difference in blood ion levels with the use of Oxinium femoral heads compared to CoCr or stainless steel heads at the 10-year follow-up [141]. In another study, metal ion levels with modular 28 mm, 36 mm, and 40 mm CoCr femoral heads indicated no difference in CoCr with increasing femoral head sizes after the 10-year follow-up [141].

Implant characteristics related to design, material combination, and type of fixation were also analyzed in the report [6]. The method of fixation was reported as a significant factor for rate of revision. Cementless fixation had a higher rate of revision than hybrid fixation and cemented fixation at different times following the index surgery. The 2022 report of the NJR [106] showed that cementless implants are still the most commonly used, although there is a downward trend in their use. The rate of revision for cemented THR was lower than that of cementless THR. The Swedish registry report [142] also revealed a similar trend. Cementless fixation was reported as the preferred method in younger and more active patients. Surprisingly, no significant difference was found in survival rates of cementless and cemented implants. Also, the outcome of 881 total hip arthroplasties in 747 aged between 9 to 21 from Norwegian, Danish, Swedish, and Finish hip arthroplasty registries merged with the dataset from the Nordic Arthroplasty Register Association (NARA) showed that both cemented and uncemented fixations seem to be a viable option in this age group, but with a lower implant survival when compared to older patient groups [143]. The AOANJRR reported that the popularity of cementless fixation has increased, leading to a decrease in the use of cemented fixation [6]. Hybrid fixation, including cemented femoral and cementless acetabular components, showed a lower rate of revision compared with cementless or all-cemented fixation. Overall, big data from the joint registries suggests that cemented fixation performs better for the >75-year-old population, but cementless and hybrid fixation performs better in younger patients [6].

The Swedish registry suggests that a head size of <32 mm has the lowest failure rate for an MoP articulation, although a 32 mm head size shows the lowest failure rate for CoP bearing surfaces. By contrast, the highest rate of failure was reported in 36 mm metal or ceramic heads with a cemented monoblock acetabular component. The outcome of 44 mm heads in MoP articulations was reported worst for cementless THRs. The 28 mm and 36 mm heads showed the worst rates of failure in CoP articulations with a cementless acetabular component [142]. The AOANJRR reports that head size affects revision rates in CoC THRs. Lower revision rates were found for a 32 mm head size compared with a 28 mm head size or less, but no difference was found between a 32 mm and 36 mm or 38 mm head in the rate of revision. The AOANJRR data is in favour of using 32 mm heads with XLPE liners. It seems that this head size or smaller shows better outcomes for standard MoP articulations, while the use of 32 mm heads is recommended for CoP articulations over smaller or larger head sizes [6].

The combination of metal with XLPE remains the most common bearing surface based on the recent Swedish registry report, although there was an upward trend of ceramic on XLPE use. Data from the Swedish registry [142] shows that MoP remains a popular bearing surface for different methods of THR including cemented, cementless, hybrid, and reverse hybrid. These days, the use of MoM bearings is limited due to the high revision rate [86]. CoC remains a popular choice for cementless THR. The 2022 NJR report [106] supports the use of CoP bearings in THR, irrespective of implant fixation method. The use of a CoP bearing is becoming more common and seems to be a better choice for hybrid hip replacement, as evidenced by low revision rates (specifically over the long term). The AOANJRR reported that modern bearings, including XLPE with metal, ceramic, or ceramicized metal heads, added to mixed ceramic on ceramic, have lower revision rates, particularly in the long term [6]. A comparison between XLPE with non-XLPE also showed that XPLE had lower rates of revision regardless of which type of femoral head was used [6,124,144,145].

It can be concluded from recent registry reports that MoP bearings provide better outcomes in the elderly population, while the use of ceramic-on-XLPE is more favourable in younger patients. In addition, registry data are biased towards the use of bearing surfaces other than CoCs [142].

4. Summary

Implant retrieval studies and joint registry data analysis of THR are multidisciplinary areas that require contributions from clinicians, engineers, and scientists. A future global direction in joint arthroplasty should aim to enhance the longevity of medical implants and minimize failures and revision rates by supporting surgeons in their decision making. Accordingly, this paper reviewed relevant retrieval studies with a focus on the effects of fretting corrosion and national joint registry reports from different countries to identify the most significant risk factors for failure in THR.

Critical patient-related risk factors such as age, gender, BMI, and ASA score were identified from our reviewed sources and presented in Table 3. The publications reviewed were selected based on parameters considered important by the authors in both retrieval studies and reports of national joint registries. Image-based parameters and factors related to patient history were not discussed in this review paper due to the lack of information in retrieval studies and joint registry reports.

We also found a large number of implant-related variables that may influence failure rates, especially by affecting the corrosion rate (Table 5). The most important implant factors affecting the results of THR are related to head size, material combination, and method of fixation. From a patient standpoint, age, gender, and BMI should be highlighted as the most significant patient-related factors that can cause early implant failure due to the effects of fretting corrosion. The role of manufacturers was also reviewed through limited available references. Based on these sources, we did not find any significant contributions to our review. Many other retrieval study factors were not analyzed due to the lack of information and, therefore, other important considerations may have been overlooked. To date, joint replacement registries have not collected a number of patient-history-based and image-based data. In the near future, it is projected that a number of other factors related to imaging data and patient reported outcome measures (PROMs) will be added to joint registries around the world to support clinicians and researchers in making evidence-based decisions in THR. The authors acknowledge the efforts by a few joint registries to implement collecting this type of data at specific follow-up timepoints following joint arthroplasty surgeries.

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