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REVIEW

A Clinical Investigation of Hip Implant Migration and Wear

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Abstract

The prediction of survival rate probability for hip implants, based on clinical data acquired before and after surgery, incorporating patient-specific parameters, represents a pivotal advancement in enabling more precise risk assessment for potential complications, such as aseptic loosening and implant wear-related inflammation, on an individualized basis. This critical step marks a substantial progression toward the realization of digitized and personalized medicine. The objective of this study was to establish prediction aiding correlations between implant wear and migration data, derived from X-ray imaging of 149 patients diagnosed with hip arthritis, and the performance of hip implants. The patients underwent cementless hip replacement surgery, receiving implants consisting of ultra-high-molecular-weight polyethylene (UHMWPE) paired with titanium-aluminum-vanadium (Ti6Al4V) wedges. Over the course of a median follow-up period of 4 years, X-ray assessments were conducted to monitor the migration of the femoral head and acetabular components using Ein Bild Röntgen Analyse (EBRA). Clinical findings revealed a linear relationship between average migration and wear. Notably, it was observed that increased cup migration corresponded proportionally to greater wear values. Furthermore, in-depth analysis revealed significant distinctions based on gender and age. Specifically, the established relationship can confidently serve as a reliable predictive model for the behavior of hip implants in female subjects and individuals aged 50–60 years.

Keywords Total hip arthroplasty · Cup migration · Wear rate · EBRA analysis · Tribology

Introduction

The most common cause of failure in total hip arthroplasty (THA) is mechanical aseptic loosening, implant instability, and migration [1, 2]. Several studies, e.g., based on stereo radiography [3–5], have demonstrated that excessive cup migration within the first two years, defined as more than 1mm or more than 2 mm at four years after surgery, are well-established risk factors for early implant failure [6–10]. The tribological properties of hip implants are also of fundamental importance for their performance and long-term survivorship. Wear or damage of the bearing surfaces is another significant risk factor for premature failures of hip implants [11–13].

Polyethylene wear is a well-known complication of hip joint replacements that causes suboptimal clinical outcomes. The phenomenon occurs when opposing surfaces in the prosthetic joint are exposed to local mechanical damage and unwanted material loss, resulting in the liberating of wear particles and debris which can lead to implant migration and failure [13]. The articulating surface between the

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femoral head and cup used in hip implants is mainly composed of Ultra-high molecular weight polyethylene (UHMWPE) paired with Ti6Al4V or stainless steel [14]. Due to the application of higher mechanical stresses and cyclic loading, sub-micron size particles of UHMWPE are generated and migrate into the surrounding area [11]. Accumulation of these particles over time may cause an eccentric position of the prosthetic head within the cup and associated risks of aseptic loosening and prosthetic component migration or instability in THA [12].

Polyethylene wear can be classified into several types including adhesive, abrasive, fatigue, corrosion, and (oxidative) wear. Sliding wear of the acetabular cup and the femoral head, however, is the main reason for implant migration. Adhesive wear stems from the transfer of the materials from polyethylene to the metal surface (like Ti alloy or stainless steel) due to frictional forces, while abrasive wear occurs when the polyethylene debris is trapped between bearing surfaces, which can act as abrasive. Fatigue wear and fretting resulting from repetitive stressing of a bearing can be also another reason for bearing wear and implant failure [15, 16].

To reduce the risk of wear-related complications, it is necessary to determine the delamination and gradual peel-off of the surface of polyethylene in vivo using serial X-ray radiographs [17].

To gain closer insights into the wear mechanisms of implants, several clinical [18] and engineering investigations [19] have been carried out in the last few years. However, these studies lack a description of definitive correlations between implants wear and migration with implant failure. Although it is widely accepted that wear is strongly affected by the coefficient of friction and the frictional behavior of the contacting surfaces [20, 21], to the best of our knowledge, a systematic correlation in hip implants has not been established yet.

Therefore, the material processing and morphological properties of the implant surfaces, which directly affect friction and wear, can also impact the prosthetic loosening and subsequent migration. Specifically, the investigation of hip plant migration and loosening has usually been carried out using the Ein Bild Röntgen Analyse (EBRA). EBRA has been demonstrated to be an accurate method for quantifying component position and orientation from radiographic measurements [22, 23], and is widely employed in THA [4–8, 24, 25]. Distal migration of the stem more than 1.5 mm detected by EBRA within the first two years is a well-established risk factor for early implant failure [26].

Using machine learning algorithms, a prediction of implant failure could be possible [27] as well as predicting liner exchange due to wear. By determining the femoral head penetration rates and discriminating them from long-term osteolysis [28] a suitable decision support for upcoming revisions might be provided. In this study, we present the results of a 4-year clinical monitoring focused on analyzing the migration of hip implants, by means of EBRA. The main objective of the work is to correlate the migration and wear data, and subsequently identify implant failures from a material and engineering perspective. To provide an engineering perspective, classical laws employed in surface mechanics were introduced. This represents a novel approach compared to previous clinical studies, which have mainly focused on the medical implications of implant migration.

Materials and Methods

The present study is an analysis of patients diagnosed with an arthritic hip between 2008 and 2016. The study received approval from the local ethics committee at the Medical University of Innsbruck, Austria. A total of 149 patients, who underwent direct anterior approach (DAA) surgery were included in the study. The patient received a cementless Accolade® II press-fit stem and a cementless Trident® press-fit cup (Stryker Co., Kalamazoo—MI, United States of America) [29–34]. The Accolade® II applied for press-fit implantations was a commercially pure plasma-sprayed titanium substrate with hydroxyapatite coating in the proximal region. The Accolade® II morphologic wedge had a size-specific medial curvature and enhanced proximal–distal proportions to mimic canal anatomy and achieve a cortical fit [35, 36]. The Trident® PSL (peripheral self-locking) cup, as a component of the acetabular implant, was a metallic shell composed of titanium alloy with a highly porous, sintered titanium coating. The inner surface of the cup was made of UHMWPE. The Trident® PSL cup was selected to allow better fixation to the peripheral lunate of the acetabulum by a 1.8 mm peripheral press-fit built into the shell [37].

Clinical assessments were performed before and after the surgery. Western Ontario and McMaster Universities Arthritis Index (WOMAC) was utilized to assess pain, stiffness, and function in patients. Medical histories were screened for sociodemographic data, surgical approach, body mass index (BMI), cut-to-suture time, and possible material failure, as well as the preoperative diagnosis for THA indication. In addition, the range of motion was recorded preoperatively and up to one year after surgery by surgeons, using a goniometer during clinical examination.

Radiological assessments were conducted at 6 and 12 months postoperatively, and then with a one-year interval. Additional images were taken if the patient had any complains. All anterior–posterior radiographs were taken in the upright position and full weight bearing at the Department of Radiology of the Medical University of Innsbruck, Austria,

Prosthetic stability and cup migration were assessed using the EBRA method [23]. To assess the migration of implants via EBRA, a minimum of three radiographs per patient were investigated at least three months of follow-up. A comparability algorithm, using a grid of transverse and longitudinal tangents of the pelvis contour, divides serial radiographs into sets of comparable ones. Through comparing the radiographs, EBRA computed the parameters of longitudinal and transverse migration of the prosthetic cup and femoral head. The migration of femoral head, acetabular cup, and wear in the horizontal and vertical directions were assessed. The 95% confidence limits for EBRA results are 1.0 mm for longitudinal and 0.8 mm for transverse migration [23, 38]. According to Krismer et al., cup loosening is defined as cup migration greater than 1.0 mm at 2 years and greater than 2.0 mm at 4 years [23]. To ensure unbiased evaluation, migration analysis was carried out by an independent investigator, who was not involved in the surgeries or postoperative treatment of patients. Figure 1 shows the reference points considered for the migration measurements from EBRA.

Statistics

The data were analyzed with Microsoft® Excel version Professional Plus 2010 (Microsoft Co., Redmond—WA, United States of America) and with GraphPad Prism version 8.0 (GraphPad Software Inc., La Jolla—CA, United States of America). All data were tested for normality using the Kolmogorov–Smirnov test. Wilcoxon matched-pairs signed rank test and Kruskal–Wallis test were applied to detect the statistically significant differences of the WOMAC scores pre- and 1-year postoperatively and EBRA measurements, respectively. A p value of 0.050 was considered a statistically significant change.

The evaluation of migration and wear of hip implants is a critical aspect of ensuring the safety and efficacy of these medical devices. As hip replacement surgeries continue to be one of the most common orthopedic procedures worldwide, there is a growing need for accurate and reliable data on the performance of hip implants [39]. Wide clinical data are essential in providing insights into the longevity and durability of these implants, as well as identifying potential issues and developing solutions to improve patient outcomes [40].

One of the most significant challenges in evaluating hip implant performance is the complex interaction between the implant and the surrounding bone and tissue [41–43]. The implant material, design, and manufacturing process can all impact the degree of wear and migration that occurs over time, and these factors can vary depending on patient characteristics and other external factors [44]. Therefore, it is crucial to collect a diverse range of clinical data to ensure that these factors are adequately considered and evaluated.

Several studies have highlighted the importance of clinical data in assessing hip implant performance. For example, a review of over 150,000 hip replacements found that the risk of implant failure was significantly higher in patients who had undergone previous hip surgery or had certain medical conditions, such as osteoporosis or rheumatoid arthritis [45]. Another study evaluated the wear and tear of metal-on-metal hip implants over time, revealing significant differences in implant performance depending on the patient's age, sex, and activity level [46, 47].

Moreover, the collection and analysis of clinical data can help identify trends and patterns in implant performance that might not be immediately apparent from individual patient cases. For example, a recent study evaluated the long-term outcomes of different hip implant materials, finding that ceramic-on-ceramic implants had the lowest revision rates after ten years [48]. Such findings

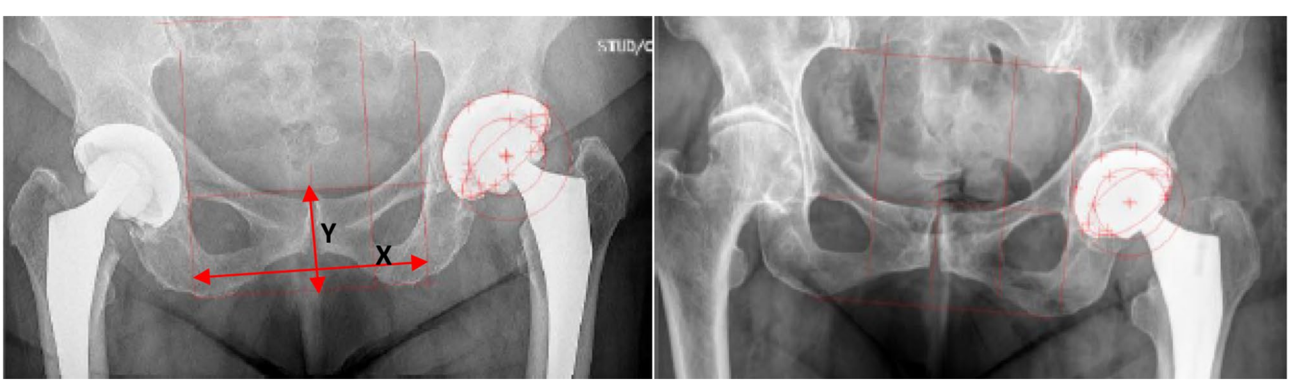

Fig. 1 Example X-ray image of a patient's hip implant with markers (in red) used as a reference for EBRA migration measurements Top of Form

can help inform future design and development of hip implants, as well as guide clinical decision-making for individual patients.

As such, continued investment in the collection and analysis of clinical data is essential to ensure the ongoing safety and efficacy of hip implants.

Results and Discussions

Collecting various patient data is crucial to assessing the wear and migration of hip implants, identifying potential factors affecting implant performance, guiding clinical decisions, and improving future implant designs. This includes demographic data (age, sex, BMI), medical history, activity level, implant-specific data (type, material, size, positioning), and radiographic data (pre and postop imaging). Patient data are important in accurately evaluating implant performance, as shown in studies that linked patient age, BMI, implant positioning, and previous surgeries to implant wear, loosening, and dislocation [15, 34–36].

Table 1 provides a comprehensive overview of the baseline characteristics of patients included in the study on hip implants. The study involved a total of 149 patients, with a gender ratio of 44.3% females and 55.7% males. The median age of the patients was 67 years, with a range of 37–87 years, while the median BMI was 26.1 kg/m^2, with a range of 15.2–37.9 kg/m^2.

In terms of surgical parameters, the median cut-to-suture time was 68 min, with a range of 33–188 min. The median cup size was 54 mm, with a range of 46–64 mm, and the head size was 32 mm in 100 cases (67%), 28 mm in 30 cases (20%), and 36 mm in 19 cases (13%).

The study followed up with patients for a mean clinical and radiological period of 4 years, with a standard deviation of 2 years. This information is essential to understanding the patient population involved in the study, the types of hip implants used, and the follow-up period for monitoring implant performance. It also provides a basis for comparison with other studies that investigate the wear and migration of hip implants in similar patient populations.

The above highlights the crucial role of comprehensive patient data collection and consideration of patient-related factors in evaluating hip implant performance. The provision of essential baseline characteristics and follow-up information aids in comprehending the study's outcomes and facilitates comparisons with related research. This meticulous attention to detail enhances the study's scientific rigor, thereby reinforcing the validity of its conclusions within the field.

Clinical Observation

Figure 2 is a graph that displays the results of the average WOMAC scores for patients divided by sex, highlighting the potential differences in pain before and one year after hip implant surgery. The results show that before surgery, men reported a smaller total WOMAC score compared to women, with an average value of 55 ± 21, while women had an average value of 59 ± 20. However, postoperatively, the trend was observed to be the opposite, with women reporting smaller WOMAC scores compared to men.

It is important to note that there was no significant correlation observed between WOMAC scores and patient age or BMI. This suggests that regardless of age or BMI, patients can experience similar levels of pain relief and functional improvement following hip implant surgery.

All the comparisons presented in the figure were statistically significant, with a p value smaller than 0.001. This indicates a high level of confidence in the results and their significance in understanding the differences in pain

Table 1 The demographics of the patients. *N* denotes the number

Sex	Male	$N = 66$
	Female	$N = 83$
Age	Mean	67
	Range	37–87
BMI (kg/m^2)	Mean	26.1
	Range	15.2–37.9
Time of surgery (Min)	Mean	68
	Range	33–188
Cup size (mm)	Median	54
	Range	46–64
head size (mm)	32.0 mm	$N = 100$ (67%)
	28.0 mm	$N = 30$ (20%)
	36.0 mm	$N = 19$ (13%)

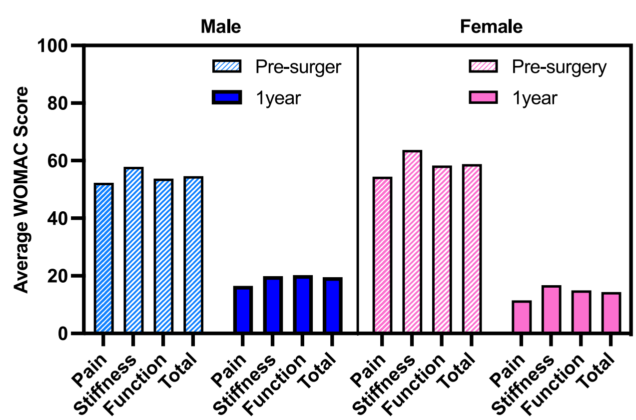

Fig. 2 Results of the average WOMAC scores, divided by men and women, reported preoperatively and 1 year postoperatively

and function between male and female patients before and after hip implant surgery.

These findings may help guide clinical decision-making regarding hip implant surgery, such as considering sex as a factor in predicting patient outcomes and tailoring postoperative care and rehabilitation accordingly. The results of this study also highlight the importance of evaluating patient-reported outcomes and considering sex as a potential confounding variable when assessing the effectiveness of hip implant surgery.

The results presented in Fig. 2 align with previous research in the literature, which has also found differences in patient-reported outcomes following hip implant surgery based on sex. For example, a study by Singh et al. [49] found that women had lower preoperative WOMAC scores compared to men but higher postoperative WOMAC scores, indicating a similar reversal in trends to what was observed in this study [50]. Similarly, a study by Amanatullah and colleagues [51] found that women had worse preoperative hip function but greater improvement in function following surgery compared to men. However, some studies have reported conflicting results, with no significant differences in outcomes between male and female patients) [52]. This may be attributed to differences in patient population, surgical technique, and implant selection.

Overall, the results presented in this study add to the growing body of literature on the importance of considering sex as a factor in predicting patient outcomes following hip implant surgery. The findings also emphasize the need for ongoing evaluation of patient-reported outcomes and the potential impact of sex on these outcomes [53].

These insights inform clinical decisions, urging sex-conscious postoperative care. The study concurs with literature showing similar sex-based shifts in postoperative WOMAC scores. Nevertheless, conflicting reports exist, possibly due to diverse demographics, techniques, and implants. This research augments sex's predictive role in hip implant outcomes, advocating consistent outcome evaluation and acknowledging sex's potential impact.

Figure 3 presents the clinical outcomes of the study before and after surgery. The results show a significant improvement in the range of motion of the hip joint after the surgical intervention. Internal rotation improved by an average of 10° ($p<0.01$), abduction improved by 8° ($p<0.0001$), and adduction improved by 6° ($p<0.05$). However, no significant differences were observed in hip flexion or external rotation before and after surgery. In addition, the comparison of leg length inequality before and after surgery did not show any statistically significant difference ($p=0.3885$).

Furthermore, the study utilized a novel method for measuring cup migration and liner wear through the use of the EBRA system. The x and y components measured through the EBRA were used to calculate the total value of the cup migration and liner wear. The equations used were

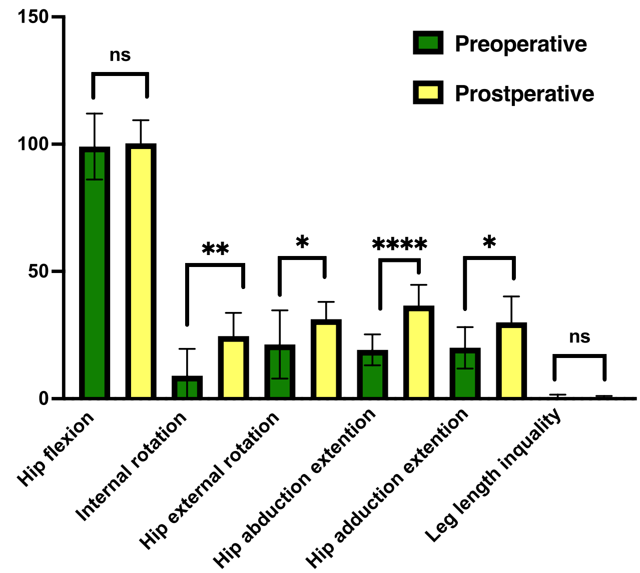

Fig. 3 Clinical outcomes of pre and postoperative conditions, * $p<0.5$, ** $p<0.01$ and **** $p<0.\ 0001$

$$\delta = \sqrt{\delta x^2 + \delta y^2} \tag{1a}$$

for migration and

$$w = \sqrt{wx^2 + wy^2} \tag{1b}$$

for wear, where δ and w represent migration and wear, respectively, and x and y denote their measured components. It is worth noting that the magnitude of migration and wear provides only an approximation of these phenomena, which are more complex and three-dimensional in reality.

Table 2 summarizes the details of the migration behavior from 6 to 48 months postoperatively, and Fig. 4 illustrates the percentages of the migrated cups divided into total migration ranges. The results demonstrate that the magnitude of cup migration increased with time, with the maximum migration occurring in the first 6 months postoperatively.

Previous research has also demonstrated the importance of measuring clinical outcomes, such as range of motion, after hip implant surgery [54]. In addition, the use of the EBRA system for measuring cup migration and liner wear has been previously reported in the literature [55]. The findings of this study provide valuable insights into the long-term behavior of hip implants, which can inform the development of more effective implant designs and postoperative care protocols.

The study highlights the importance of considering multiple factors, including clinical outcomes and implant behavior, when evaluating the effectiveness of hip implant surgery. These findings can inform clinical decision-making and improve patient outcomes following hip implant surgery.

Table 2 Average values of total cup migration, from Eq. (1a), during the follow-up period

Months postoperatively		6	12	18	24	36	48
Number of migrated implants		99	98	28	88	74	39
Migration (mm)	Mean	0.54	0.89	1.10	1.19	1.32	1.36
	SD	0.53	0.81	0.88	1.12	1.25	1.02
	Median	0.40	0.74	0.98	0.86	1.00	1.10
	Range	0.00–2.94	0.00–4.06	0.20–4.50	0.00–7.12	0.00–8.26	0.00–4.06

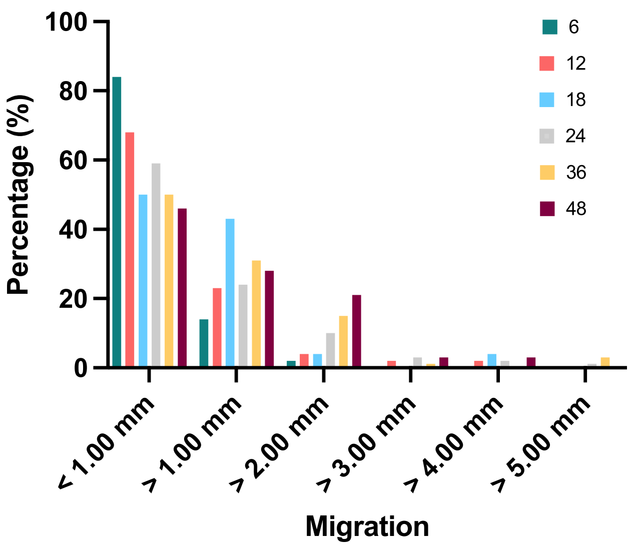

Fig. 4 The percentage of implants showing cup migration during the follow-up period

The results presented in Fig. 3 of the study indicate significant improvement in range of motion (ROM) in patients following hip implant surgery, with statistically significant improvements observed in internal rotation, abduction, and adduction. These findings are consistent with previous research in the literature, which has demonstrated the benefits of hip implant surgery for improving ROM in patients with hip joint diseases or injuries [56–58]. However, the lack of significant differences observed in hip flexion and external rotation before and after surgery is somewhat surprising and warrants further investigation.

The results of our study also suggest that leg length inequality does not change significantly following hip implant surgery. This finding is consistent with several previous studies that have investigated leg length inequality after hip implant surgery [59, 60]. However, it is worth noting that leg length inequality can be a significant source of patient dissatisfaction and should be carefully evaluated and addressed by the surgeon in the preoperative planning phase [61].

The calculation of cup migration and liner wear using the EBRA method described in the study is a useful technique for evaluating the long-term stability and wear of hip implants. Previous studies have also used similar methods to assess implant migration and wear over time [62]. The results presented in Table 2 and Fig. 4 of the study suggest that the cups migrated to varying degrees over the 48 months postoperatively, with most cases falling within the 0.0–1.0 mm range. These findings are consistent with previous research demonstrating that cup migration can occur in the first few years after surgery but tends to stabilize over time [61, 63, 64].

Cup migration after hip implant surgery is a common phenomenon, and it is believed to be related to the initial healing process and bone re-modeling. During the first few months after surgery, the implant is still integrating with the surrounding bone tissue, and this process may cause some initial movement or settling of the implant, leading to migration. However, over time, the implant and bone tissue continue to integrate and remodel, resulting in a more stable implant-bone interface. As a result, the rate of migration tends to decrease after the initial healing period. Additionally, the fixation method used during surgery can also play a role in the extent and pattern of cup migration. For example, cementless fixation may result in greater initial migration but better long-term stability, while cemented fixation may result in less initial migration but greater long-term risk of loosening [41–43].

It's worth noting that while some degree of cup migration is normal and expected, excessive or persistent migration can lead to implant failure and the need for revision surgery. Close monitoring and early detection of migration are important to prevent long-term complications.

The results presented in this study add to the existing literature on the benefits and potential complications of hip implant surgery. The findings support the use of hip implant surgery as a safe and effective treatment for improving ROM in patients with hip joint diseases or injuries. However, further research is needed to better understand the factors that influence hip flexion and external rotation after surgery and to develop strategies for minimizing the risk of leg length inequality [59].

Table 3 presents the results of the cup migration observed during the four-year postoperative study. Aseptic loosening was defined as migration greater than 1.0 mm after 2 years

Table 3 Percentage of cups migration (*N* denotes the number of cups) at 2 and 4 years postoperatively

Migration range	Year 2	Year 4
> 2.00 mm	41% ($N=36$)	26% ($N=10$)
1.00–2.00 mm		74% ($N=29$)
< 1.00 mm	59% ($N=52$)	

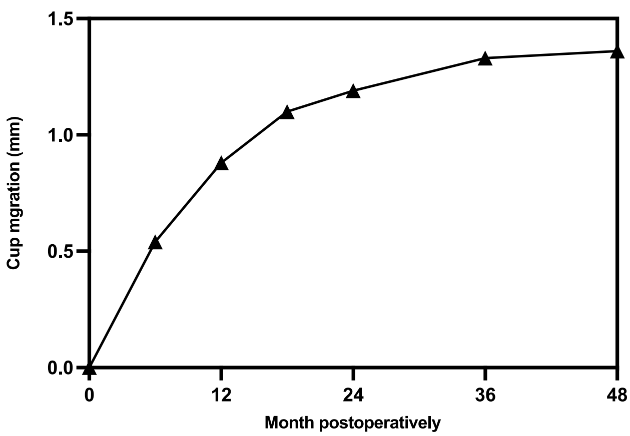

Fig. 5 Average value of cup wear as a function of time (months postoperatively)

[23]. Based on this definition, 36 out of 88 cups (i.e., 41%) showed migration greater than 1.0 mm after 2 years. After 4 years, 39 cups had sufficient EBRA follow-up to determine the migration behavior, and out of these, 10 cups (26%) migrated more than 2.0 mm. Additionally, nearly 74% of the investigated cups showed a migration smaller than 2 mm.

Figure 5 shows the average value of cup migration, as determined through Eq. (1a), plotted as a function of time. The results indicate that cup migration tends to increase with time, often in a linear or quasi-linear manner. In general, cup migration is more evident in the first 6–12 months postoperation, with the migration rate reducing after that. However, there is still a significant risk of cup migration even after the first year, and this can lead to aseptic loosening, implant failure, and the need for revision surgery.

Figure 6 presents a representative X-ray image demonstrating cup migration. The image displays a femoral head that has shifted out of alignment with the cup, highlighting the potential complications associated with cup migration.

These findings are consistent with previous studies that have also reported the occurrence of cup migration following hip implant surgery and the potential risks associated with aseptic loosening [65, 66]. However, the results of this study provide valuable insights into the long-term behavior of cup migration and the need for continued monitoring of patients postoperation to detect any signs of implant failure or complications.

The results presented in Table 3 and Fig. 5 are significant because they provide valuable information on the long-term stability of hip implants, which is essential for predicting implant survival and reducing the risk of revision surgery. The finding that 41% of cups showed migration greater than 1.0 mm after 2 years, and 26% of cups migrated more than 2.0 mm after 4 years, highlights the need for close monitoring of patients with hip implants in the years following surgery.

It is important to note that although most of the cups showed a migration smaller than 2.0 mm, even small amounts of migration can lead to mechanical failure, pain, and discomfort. Therefore, it is essential to monitor cup migration over time to detect early signs of implant failure and take appropriate action to prevent further damage.

The X-ray image in Fig. 6 demonstrates a femoral head that has shifted out of alignment with the cup, which can cause significant pain and discomfort for the patient. This highlights the importance of identifying and addressing cup migration as early as possible to prevent such complications and improve patient outcomes.

The results presented in Table 3 and Fig. 5 provide valuable information on the long-term stability of hip implants and the need for close monitoring of patients in the years following surgery. By identifying and addressing cup migration

Fig. 6 X-ray images showing an acentric head in a cup, which is a sign of liner wear and migration of the cup. Images obtained with permission from the Medical University of Innsbruck, Austria

early, clinicians can improve patient outcomes and reduce the risk of revision surgery.

In the detailed examination of cup migration in male and female subjects (as shown in Fig. 7), it was observed that females displayed a comparatively lower mean migration of the cup compared to males. Notably, both males and females exhibited comparable average ages, with females averaging 65.5 ± 10.1 years and males averaging 63.4 ± 11.8 years. The average cup migration for females was measured to be up to 0.4 mm, whereas males showed a notably higher average cup migration of up to 1.4 mm.

Figs 8 and 9 depict the average wear values over the 4-year study period, analyzed both individually (unisex) and separately by gender. The results indicate that the average wear gradually increased up to 0.5 mm. Females exhibited a notably higher level of cup wear (with measurements of up to 1.6 mm after 4 years) compared to males, who showed an average cup wear of 0.4 mm.

The study found that females had a lower mean migration of the cup compared to males, despite comparable average ages between the two groups. The average cup migration for females was up to 0.4 mm, while males had a notably higher average cup migration of up to 1.4 mm. Furthermore, females exhibited significantly higher levels of cup wear, with measurements of up to 1.6 mm after 4 years, compared to males with 0.4 mm.

These findings are consistent with previous studies that have also reported differences in cup migration and wear rates between male and female patients. One possible explanation for these differences is that females tend to have smaller acetabular bone size compared to males, which could lead to a reduced surface area for the implant to anchor onto, resulting in greater potential for loosening and migration. Additionally, hormonal factors may also contribute to differences in bone density and remodeling between the sexes, which could affect implant stability and wear rates [43].

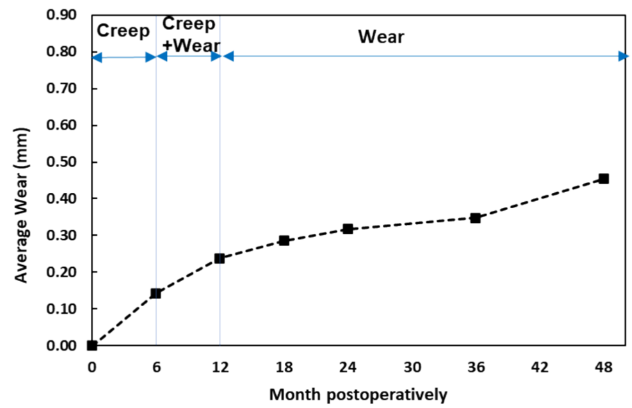

Fig. 8 Average value of cup wear as a function of time (months postoperatively)

It is important to note that while this study provides valuable insights into the behavior of cup migration and wear in male and female patients, it is limited by the relatively small sample size and short follow-up period of 4 years. Future studies with larger sample sizes and longer follow-up periods are needed to confirm these findings and further elucidate the underlying factors contributing to these sex-based differences.

Figure 10 demonstrates an attempt to establish a correlation between the average migration and wear of the cup, as computed using Eqs. (1). The results showed that the two quantities could be well-fitted with a linear relationship, where the slope was found to be 0.2414 and the R2-value was 0.9987. This linear relationship was also intuitive, as longer displacements (i.e., larger migration values) led to proportionally larger wear values. Furthermore, this result

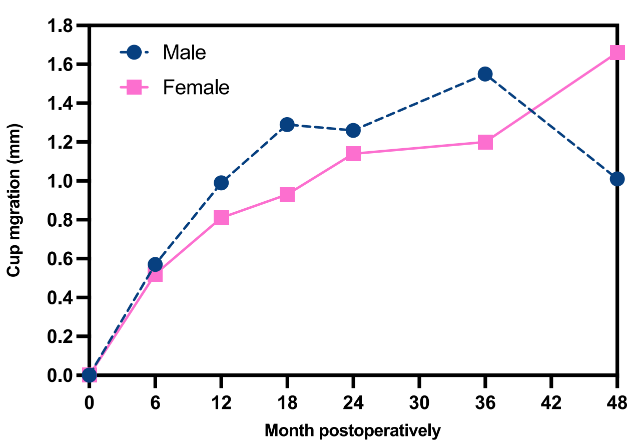

Fig. 7 Average value of migration as a function of time (months postoperatively), from EBRA identified by sex (female = pink lines, male = dashed blue line)

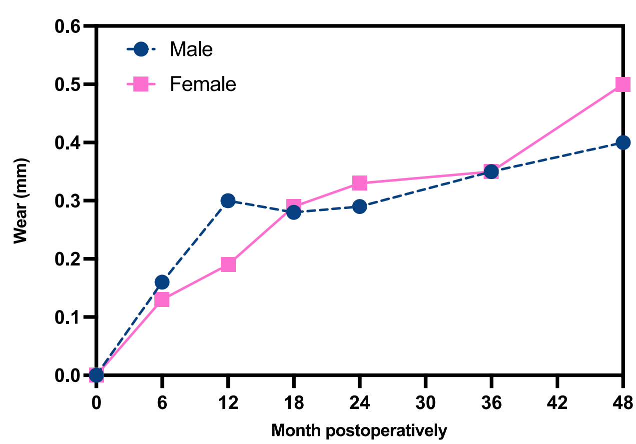

Fig. 9 Average value of wear as a function of time (months postoperatively), from EBRA identified by sex (female = pink lines, male = dashed blue line)

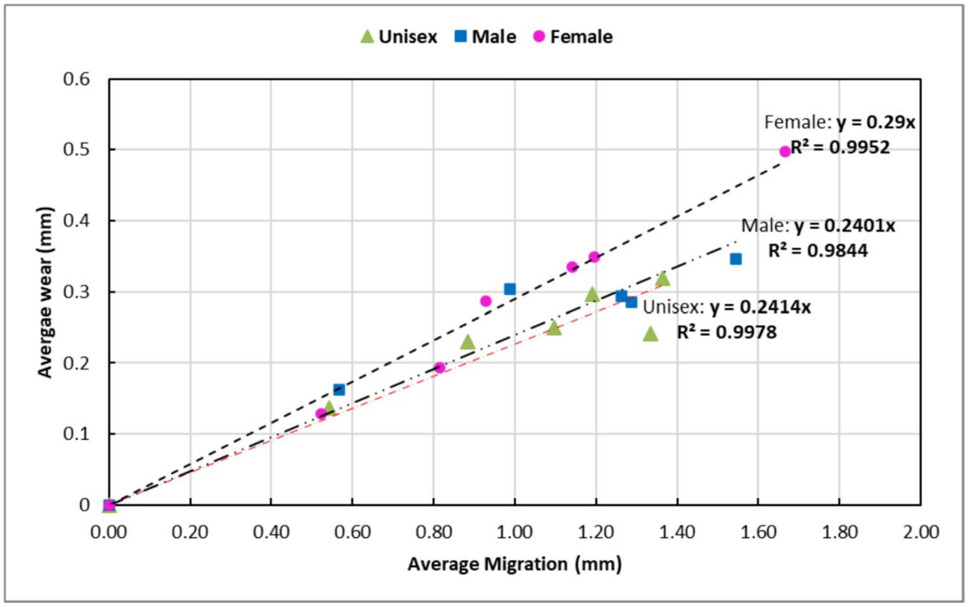

Fig. 10 Average magnitude of head wear vs. average magnitude of cup migration in the first 48 months postoperatively, from EBRA for distinct gender groups and a combined individual group

was also consistent with Archard's classical wear law [67], which suggests that the worn volume of material (V) is proportional to the product of the applied normal load (P), sliding distance (L), and the hardness of the contacting surfaces (H).

It is worth noting that the magnitude of cup migration can be interpreted as a sliding distance. By applying the variables introduced in Eqs. (1), it can be assumed that $V{-}w$, and thus, the linear relation in Fig. 10 can be retrieved, i.e., $w - \delta$. However, while Eq. (2) provides an initial approximation of the relationship between cup migration and wear, more complex and realistic models may be necessary to accurately capture the dynamics of these phenomena.

It should be emphasized that these findings need to be interpreted with caution, as the actual conditions in the joint could vary from the simplified assumptions made in Eq. (2). For instance, the load distribution and occurrence of non-uniform wear may significantly affect cup migration and wear. Therefore, more research is needed to understand the relationship between cup migration and wear in a more comprehensive and realistic manner.

The results of this study provide important insights into the behavior of hip joint replacements and the factors that affect their performance. By analyzing the migration and wear of the acetabular cup in male and female patients over a four-year period, the study identified significant differences in the behavior of the implants based on gender.

One of the key findings was that females displayed a lower mean migration of the cup compared to males. This suggests that there may be differences in the way the hip joint functions in males and females, which could have important implications for the design and development of hip implants. Similarly, the finding that females exhibited higher levels of cup wear compared to males suggests that there may be differences in the way that the hip joint functions in males and females affect the longevity and durability of hip implants [43, 68].

The study also found a linear relationship between cup migration and wear, which is consistent with the classical wear law proposed by Archard [67]. This provides important insights into the underlying mechanisms of wear in hip implants and can be used to inform the development of more accurate and realistic models to predict the behavior of hip implants over time.

The impact and significance of these results lie in their potential to improve the design and development of hip implants, ultimately leading to better outcomes for patients undergoing hip replacement surgery. By identifying factors that affect the performance of hip implants, such as gender differences and wear behavior, researchers and engineers can work to develop more effective and durable hip implants that are better suited to the needs of patients. This can improve patient outcomes, reduce the need for revision surgery, and ultimately improve the quality of life for patients with hip joint issues.

The meticulous examination of the data based on gender indicates that there is no significant difference between the wear and migration of female patients and the overall analysis without considering gender. This finding implies that gender is not a significant factor in predicting or identifying prosthetic wear and migration. However, it is worth noting that this analysis is based on a specific dataset, and further research may be needed to investigate the relationship between gender and prosthetic wear in different populations.

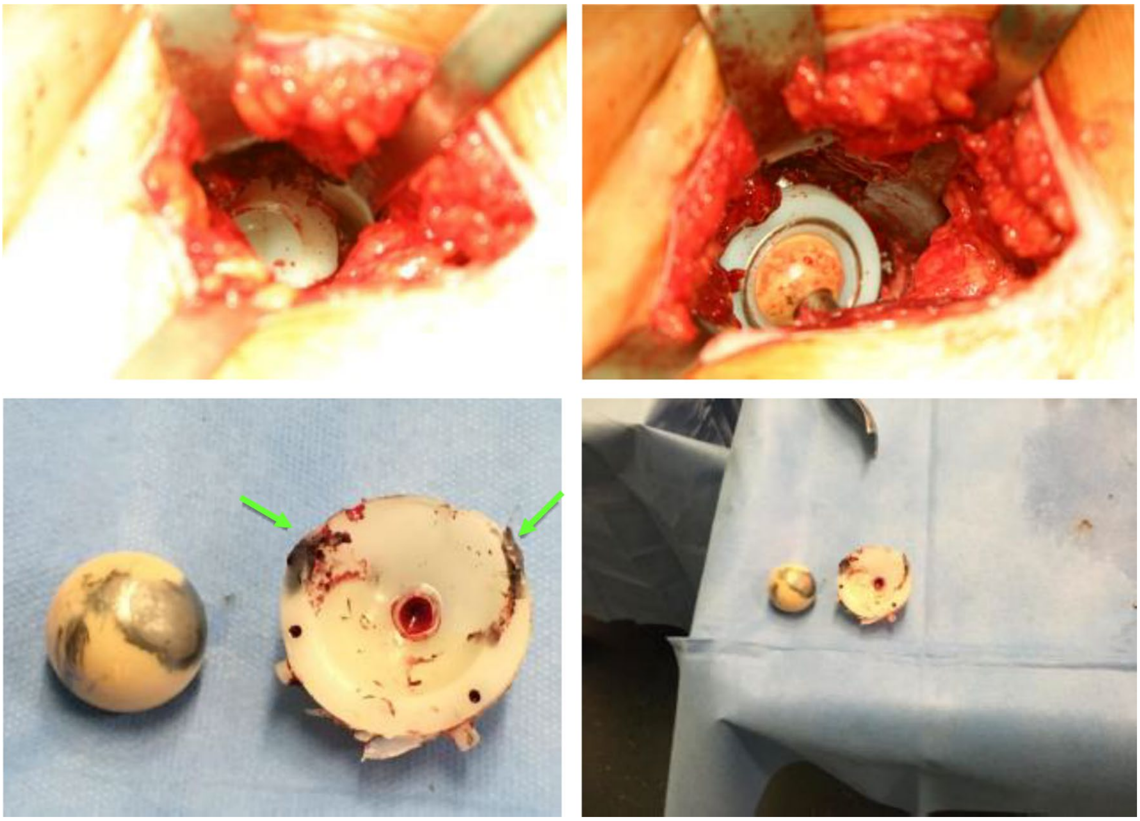

Fig. 11 Example hip implant postoperation, including the femoral head (left) and the liner (right), showing severe signs of wear. Images obtained with permission from the Medical University of Innsbruck, Austria. Photograph of a postoperation hip implant with severe material wear: femoral head (left) and liner (right)

Figure 11 illustrates the impact of material wear on prosthetic devices. The presence of black areas in the metal debris removed during abnormal contact conditions suggests severe wear patterns and signals, which can have detrimental effects on the integrity of the metal cup and pose a risk to patients' health [69]. This highlights the importance of monitoring prosthetic devices and detecting any signs of wear or malfunction, which can lead to complications and require further medical intervention.

In summary, the statement emphasizes the importance of carefully monitoring prosthetic devices and detecting any signs of wear or malfunction, regardless of the patient's gender. It also highlights the potential risks associated with prosthetic wear and underscores the need for continued research to improve prosthetic device design and performance.

Age	30–40	40–50	50–60	60–70	70–80	80–90
Pearson's correlation coefficient	0.340554	0.970988	0.990578	0.898982	0.945916	0.839385
sample size	3	12	33	48	42	8

Figure 12 presents the scatter plots that illustrate the relationship between head wear and cup migration for various age groups. Upon visual inspection of the scatter plots, it is evident that the group aged 50–60 exhibits a similar trend to that of the combined individual group, indicating a strong correlation between head wear and cup migration.

Pearson's correlation coefficient values were calculated for each age group to quantify the strength of the correlation between head wear and cup migration. The results showed that there is a statistically significant correlation between head wear and cup migration for all age groups, except for the 30–40 age group. This age group showed a weaker

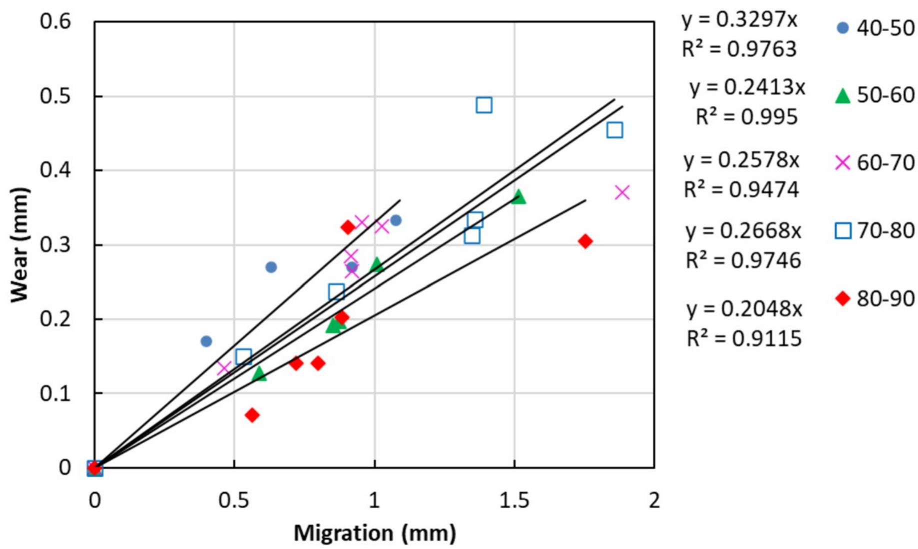

Fig. 12 Average magnitude of head wear vs. average magnitude of cup migration in the first 48 months postoperatively, from EBRA for different groups of ages

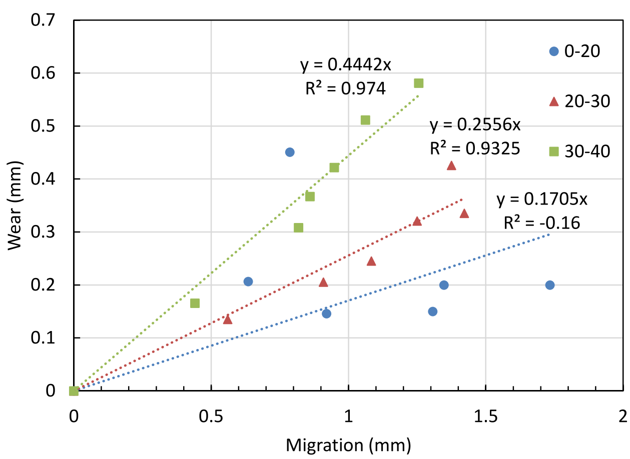

Fig. 13 Average magnitude of head wear vs. average magnitude of cup migration in the first 48 months postoperatively, from EBRA for different groups of BMI

correlation compared to other groups, although the sample size for this group was relatively small.

The correlation coefficient values for each age group indicate the slope of the regression line, which provides an estimate of the strength and direction of the correlation between the two variables. The slope of 0.24 indicates a positive correlation between head wear and cup migration, with a greater degree of wear leading to a larger degree of cup migration.

IBM	0–20	20–30	30–40
Pearson's correlation coefficient	0.2874	0.9668	0.9890
sample size	7	7	7

These findings have important implications for the design and use of prosthetic devices, as they suggest that wear can significantly impact the stability and function of the device. It is important to monitor wear over time and to take steps to minimize wear, such as using high-quality materials and optimizing the fit of the device. Furthermore, the findings suggest that different age groups may exhibit different rates of wear and cup migration, which could inform the development of more tailored prosthetic devices for different patient populations.

Figure 13 presents the scatter plots that illustrate the relationship between head wear and cup migration for various BMI groups. Notably, the group with BMI values of 20–30 exhibited trends that are similar to the combined individual trend, indicating a strong correlation between head wear and cup migration.

The Pearson's correlation coefficient values were calculated for each BMI group to quantify the strength of the correlation between head wear and cup migration. The results showed that there is a statistically significant positive correlation between head wear and cup migration in groups with 20–30 and 30–40 BMI groups.

These findings have important implications for the design and use of prosthetic devices, as they suggest that BMI can significantly impact the stability and function of the device. It is important to monitor wear over time and to take steps to minimize wear, such as using high-quality materials and optimizing the fit of the device. Furthermore, the findings suggest that different BMI groups may exhibit different rates of wear and cup migration, which could inform the development of more tailored prosthetic devices for different patient populations.

It is important to note that BMI is not the only factor that can impact the wear and function of prosthetic devices. Other factors such as age, activity level, and underlying health conditions can also play a role. Therefore, it is important to take a holistic approach to prosthetic device design and use, taking into account a range of factors to optimize the device for each individual patient.

Total hip arthroplasty (THA) is a highly successful surgical procedure and has been widely recognized as the "operation of the century" [56, 57]. However, despite its high success rate, complications can still occur, and reducing the need for implant replacement is an essential goal for improving patients' quality of life. Implant loosening and movement can result in material wear and/or irreversible damage, emphasizing the significance of analyzing real patient data pre- and postoperatively to predict potential complications for regulatory and insurance purposes [60–62]. To perform this analysis, crucial patient information such as age, sex, BMI, and health status, along with pre- and postoperative X-ray images and material characterization, should be considered.

The assessment of hip implants, both in terms of technology and regulation, relies heavily on surgical experience. However, relying solely on intuition and experience to analyze clinical data can lead to subjective conclusions. Additionally, the evaluation of THA outcomes using the WOMAC score or the Harris Hip Score (HHS) has been shown to be inconsistent and poorly reported due to various factors. While these scores provide important feedback for hip replacement surgeries, they are unreliable tools for health technology assessment or implant condition evaluation.

In this context, the use of EBRA, which extracts data from images, can provide valuable information for predicting possible implant failure. However, the quality of the data depends on the quality of the radiation equipment and imaging procedure used. It should be noted that EBRA data alone may not be sufficient for a unique and critical assessment, but it is a crucial component for constructing a robust and reliable database.

In addition to patient data, tribological conditions of the surfaces in contact are a significant part of a comprehensive database, including information on material hardness, roughness, wear, etc., and their variations over time. As mentioned earlier, analytical relationships between measured migration and wear are available, and more complex models can be developed with sufficient data [20].

To provide a complete picture of implant failure, an extensive characterization of removed implants should be performed. Although materials used for manufacturing hip implants are considered biocompatible and show negligible corrosion in the body environment under static conditions, mechanically assisted corrosion can occur during body movements [43, 70]. This phenomenon can have adverse effects on both the body and the implant surface. The surface of the implant can deteriorate, leading to the release of metal species into body fluids, resulting in adverse local tissue reactions known as "metallosis" or "metal poisoning." It has been estimated that metal poisoning is a leading cause of at least 5% of prosthetic replacements [48].

Future research studies focused on the material performance of hip implants should be devoted to a more detailed characterization of the material properties and morphology of the replaced implants (e.g., by means of microscopy techniques).

Wyss et al. [14] conducted a five-year clinical study on 50 patients with primary osteoarthrosis who were treated with uncemented cups. Their results showed a mean migration of 0.082 mm after 2 years and 1.25 mm after 5 years. The migration rate, however, reduced with an annual rate of 0.09 mm/year.

De Smet et al. [71] studied the relationship between linear wear and acetabular cup migration in metal-on-metal hip resurfacing. They did not employ direct measurement techniques to quantify wear, but alternatively, the levels of metal ions in the blood and urine of patients were used as an indicator of wear. Their result showed that higher levels of metal ions were associated with greater cup migration.

The linear wear rate of conventional polyethylene used in THA is between 0.06 to 0.08 mm/year. The three-dimensional measurement of wear obtained by radiostereometric analysis (RSA) also demonstrated mean wear of 0.41 mm over a five-year period [72].

Comtesse et, al. [73] examined the migration of uncemented Vitamin E-infused Highly cross-linked polyethylene acetabularcup for 253 patients over a period of 2 to 5 years. Their results indicated an annual migration of 0.05 mm/y. They also monitored the wear rate over the period and their results showed the annual wear rate of 0.025mm/y.

Previous study with demonstrated the sex-related differences in acetabular cup migration. An analysis of longitudinal sagittal cup rotation revealed that female subjects presented greater average cup inclination compared to males ones [74].

A stable acetabular cup fixation as well as tribological properties of hip implants are of fundamental importance for their performance and long-term survivorship. Two out of three causes of hip implant revision surgeries are related to implant instability/dislocation (22%) and mechanical loosening (20%), and the other factor is infection (15%).

Conclusions

This investigation presents a novel approach to the analysis of hip implant migration, incorporating classical principles from surface mechanics to provide a material-oriented perspective. The outcomes of this research unequivocally establish a linear correlation between average implant migration and wear, unequivocally demonstrating that heightened cup migration correlates with increased wear rates over time. By offering an extensive repository of follow-up data utilizing EBRA and the development of a prediction model encompassing multiple implant variations, the prospect of constructing a predictive model for cup migration and acetabular implant wear rates becomes feasible. This information holds significant clinical utility, particularly in the decision-making process concerning whether a liner exchange or complete cup revision is warranted for a given patient. These findings can serve as foundational insights for the refinement of future hip implant designs, with the overarching aim of enhancing their durability and mitigating the necessity for revision surgeries. Nevertheless, it is imperative to underscore the necessity for further investigations to elucidate the influence of variables such as cup sizes and diverse cup types on the predictive capabilities of the cup migration model. The discernment of which parameters within the prediction model, such as cup size and type, warrant consideration is of paramount importance for advancing our understanding in this domain.

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Declarations

Conflict of interest The authors declare no conflict of interest related to this study.

Informed Consent Informed consent was obtained from all participants prior to their involvement in the study.

Human and Animal Rights Declaration This study was conducted in full compliance with ethical guidelines for human and animal research, ensuring all ethical principles were upheld.

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