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Corrosion of the Head-Stem Taper Junction—Are We on the Verge of an Epidemic?

Review Article

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Abstract *Background:* The modular head taper junction has contributed to the success of total hip arthroplasty (THA) greatly. Taper corrosion and wear problems reported for large and extra-large metal-on-metal bearings as well as for bi-modular THA stems have cast doubt on the benefit of the taper interface. Presently, corrosion problems are being reported for nearly all kinds of artificial hip joints incorporating metal heads, questioning taper connections in general. *Questions/purposes:* This study aimed to review the mechanical and electrochemical relationships that may lead to taper corrosion, which have been reported more commonly in recent literature, and to also review the contribution of patient characteristics and surgical techniques involved in taper assembly that may contribute to the problem. *Methods:* The search criteria "(corrosion) AND (hip arthroplasty) AND (taper OR trunnion)" and "(hip arthroplasty) AND ((pseudotumor) OR (pseudo-tumor))" in PubMed and the JAAOS were used for the literature search. In addition, the arthroplasty registers were considered. *Results:* Most studies acknowledge the multifactorial nature of the problem but concentrate their analysis on taper and implant design aspects, since this is the only factor that can be easily quantified. The sometimes conflicting results in the literature could be due to the fact that the other two decisive factors are not sufficiently considered: the loading situation in the patient and the assembly situation by the surgeon. All three factors together determine the fate of a taper junction in THA. There is no single reason as a main cause for taper corrosion. The combined "outcome" of these three factors has to be in a "safe range" to achieve a successful long-term taper fixation. *Conclusion:* No, this is not the beginning of an epidemic. It is rather the consequence of disregarding known mechanical and electrochemical relationships, which in combination have recently caused a more frequent occurrence—and mainly reporting—of corrosion issues.

Keywords taper · corrosion · fretting · contamination · assembly · loading · cobalt · chrom · ions · titanium alloy

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Introduction

The attention presently paid to the taper junction of modular total hip replacements (THR) at meetings and conferences is tremendous. This interest started with the problems associated with the use of large heads (36 mm and greater) in metal-on-metal (MoM) bearing articulations in THR. These designs were introduced early in the twenty-first century as a revision option for resurfacing prostheses that had failed by femoral neck fracture. This option also allowed physicians, who wanted to achieve better stability against dislocation, the use of large-diameter bearings without the increase in wear associated with larger heads against polyethylene (PE) [31]. Joint registries have shown that despite the advantages demonstrated by simulator data, this concept did not work well in the clinical setting. In 2015, the National Joint Registry of UK and Wales reported a cumulative probability of 15.69% for revision of the most commonly used uncemented stem with a MoM bearing articulation at 10 years after implantation [38]. In contrast, with the same stem (and taper) with a metal-on-polyethylene (MoP) bearing articulation had a revision rate of to 4.47% and with ceramic-on-polyethylene (CoP) only 2.19% [38]. The Australian registry reports only 0.7% of all primary THA revisions to be due to a metal-related pathology, excluding all procedures with MoM articulations larger than 32 mm [1]. In the supplementary report of the Australian registry on MoM bearings above 32 mm, metal-related pathologies are responsible for 41.2% of the revisions [2]. This data helps to clarify the source of the metal corrosion in MoM THR. MoM bearings with femoral head diameters above 32 mm lead to high friction in unfavorable lubrication situations [5]. This problem is not related solely to MoM THR's but also to any large-diameter THR. The taper interface should be vigilantly inspected during revision of all bearing articulations and signs of corrosion documented, even if the reason for revision is PE wear and not a metal-related pathology [19].

The first report of corrosion between mixed metal THA components dates back to 1981 [35]. Interestingly, in this paper, it was also stated that "no exaggerated in vivo corrosion due to the coupling of these cobalt and titanium alloys" was found. Furthermore, around the same time, cobalt (Co) and chrome (CR) concentration elevations in serum after THA were demonstrated for CoCr Monobloc stems against cemented PE cups [3, 8], demonstrating that CoCr always corrodes in the body even without a mixed metal implant combination or a taper articulation. However, taper problems were common in hip joint bearings against PE; the overwhelming success of this design of arthroplasty would not be possible.

The purpose of this review is to identify and discuss the combined influence of the contributing factors that together create the mechanical loading situations and possible corrosion at the head taper junction in THA. The problem of MoM bearings will not be the focus of this review. The problems associated with this kind of bearing articulation have been extensively addressed elsewhere [16, 22, 24, 37]. It is also not our purpose to review the clinical treatment of patients with metal-related pathologies in bearings utilizing PE as a bearing partner as other authors have presented very comprehensive reviews addressing this issue [28]. It is the goal of this review to offer possible explanations for the recent increased incidence of observed taper-related corrosion problems and to suggest measures to reduce the rates of this phenomenon.

Methods

PubMed and the Journal of the American Academy of Orthopedic Surgeons were used for the literature search. The search criteria "(corrosion) AND (hip arthroplasty) AND (taper OR trunnion)" yielded 160 hits, and the search criteria "(hip arthroplasty) AND ((pseudotumor) OR (pseudo-tumor))" 172 hits. All hits were manually scanned in order to identify the relevant publications. In addition, the National Registries of Australia as well as the Registry of UK, Wales, and Scotland were used. Selected studies referenced in the publications identified were also considered.

Results

History

Taper corrosion has been documented since the early days of modular THA systems, when it was also related to catastrophic biological consequences. The first occurrence of a pseudo-tumor related to taper corrosion for a Lord stem with a CoCr-PE bearing articulation was reported by Svensson and co-workers in 1988 [46]. The images in their paper look very similar to the images in recent publications. More than 10 years later, Goldberg and co-workers attributed the observed corrosion to fretting and mechanically assisted crevice corrosion, mainly occurring at the female taper inside the head [18]. They identified the flexural rigidity of the neck as one predictor for the extent of corrosion observed. What has happened since? Necks and tapers have been made smaller and shorter, reducing their flexural rigidity (Fig. 1) [43]. This development has been accompanied by a simultaneous increase in head diameters to reduce dislocation (Fig. 1), which seemed to be justified due to the improved wear characteristics of the newer cross-linked and anti-oxidative stabilized PEs. This development was further accompanied by a continuous increase in the obesity rates in most populations, reaching 36.3% in the US population (Fig. 2) [8] [15].

These three developments together with changes in other factors, which will be discussed in this review, have increasingly challenged the taper fixation strength, resulting in the corrosion problems observed. Two prerequisites are necessary for fretting and crevice corrosion to occur: relative motion between the components and the presence of fluid. Since fluid is always present around the hip joint, the way to minimize fretting and crevice corrosion is the restriction of the relative motion at the taper interface [17]. This can be achieved by simultaneously addressing three decisive factors: taper design, loading, and assembly.

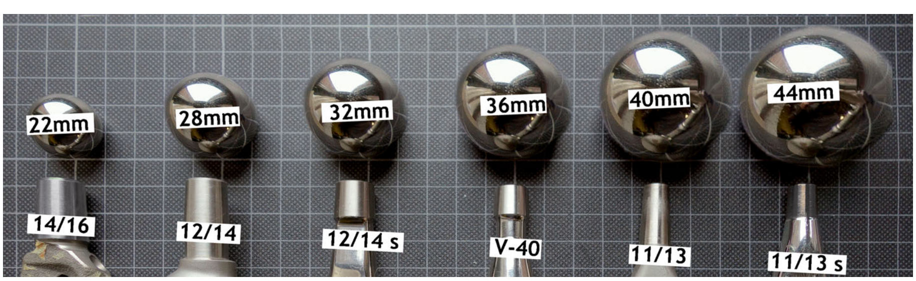
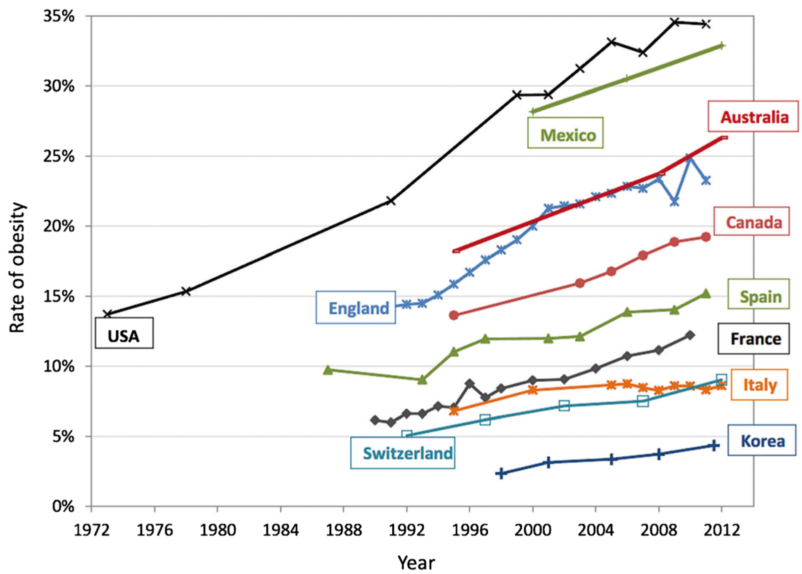


Fig. 1. Change of taper dimensions and head diameters during the last 25 years. The arrangement is not according to temporal development but rather from smallest to largest for heads, re. largest to smallest for the tapers.



Note: Age- and gender-adjusted rates of obesity and overweight, 2005 OECD standard population. Measured height and weight in Australia, England, Korea, Mexico and the United States; self-reported in other countries. No projections were produced in 2010 for Australia, Mexico and Switzerland.

Fig. 2. Development of obesity rates in selected countries (reproduced with permission from Obesity Update OECD Directorate for Employment, Labour and Social Affairs, June 2014).

Taper Design, Implant Configuration and Loading

Taper surface morphology (rough or smooth) has been shown to influence the amount of corrosion observed, but the data are still insufficient to draw definite conclusions [40]. Taper diameter was also shown to play a role: thinner tapers show more corrosion [48]. Longer heads, larger heads, varus stems, and higher offset stems show more fretting and corrosion [12–14, 33, 41]. Despite the clear influence of parameters demonstrated to increase the loading of the taper, corrosion has been shown for nearly all taper designs and implant configurations [28]. Several studies have shown that the problem is greatly reduced when ceramic heads are used [30, 47, 51]. Caution is advised in using ceramic heads with titanium sleeves in the primary situation. Introducing such an additional interface is necessary in revision surgeries, if a new ceramic head is placed on a pre-used male taper [20]. It is not indicated in primary surgeries.

Tapers are used in engineering for the transfer of loads applied along the taper axis (Fig. 3a). Loads applied off-axis—as is the normal situation for the taper connection between head and stem in THA—cause non-symmetrical compressive radial stress distributions (Fig. 3b–d). The radial stresses are generated by the superposition of "toggling" (rotation) stresses (distribution is assumed linear) due to the joint force and "press-fit" stresses due to the impaction force [7]. The head length as well as joint friction moments increase the non-symmetrical distribution of these stresses, leading to micro-motions or even a loss of contact in the worst case due to the difference in stiffness of the materials used (Fig. 3). A cyclical loss of contact is related to micro-motions and "gap" opening, allowing fluid to enter the interface. The resulting material loss due to fretting and corrosion can then be identified on the female taper inside the head (Fig. 4).

Patient activities and body weight increase the moment on the taper junction similarly to that shown in Fig. 3 [4, 27].

Assembly

Three main taper designs have evolved over the years: the 12/14 "Euro"-taper, the "V-40"-taper, and the "Type I" taper. Other tapers such as the 14/16 taper, the 11/13 taper, and the C-taper are also still available but the numbers are small. The 12/14 taper is used by several companies, whereas the Type-I and V-40 tapers are each used by only one company. The problem of the common name Euro or 12/14 taper is that each company has defined its own specifications based on the desired taper angle difference between male (stem) and female (head) taper. This means that heads and stems, despite all being labelled with the same name, are not interchangeable between companies [50]. The "true" 12/14 taper with diameters of 12 mm proximally and 14 mm distally is defined for a taper length of 2 cm and yields a taper angle of 5.725°. The actual values with the respective tolerances of the different companies are not officially known and neither are the specifications for the taper surface morphology (Fig. 5). Attempts to standardize the taper specifications by ISO and DIN have failed since the companies were afraid that this would encourage users to combine components from different manufacturers, which have never been tested in this combination. Some companies even sell one specific implant types with two different taper sizes. The only safe solution to this confusion is a simple one: heads should only be used on the intended stems as it is required by the instructions for use of the same manufacturers. "Major" mismatch refers to the combination of a head and stem with different taper designs, such as a 14/16 head on a 12/14 stem [29]. Minor mismatch (same "type" from different manufacturers) has been shown to cause clinical problems in some cases, and it remains unclear as to which

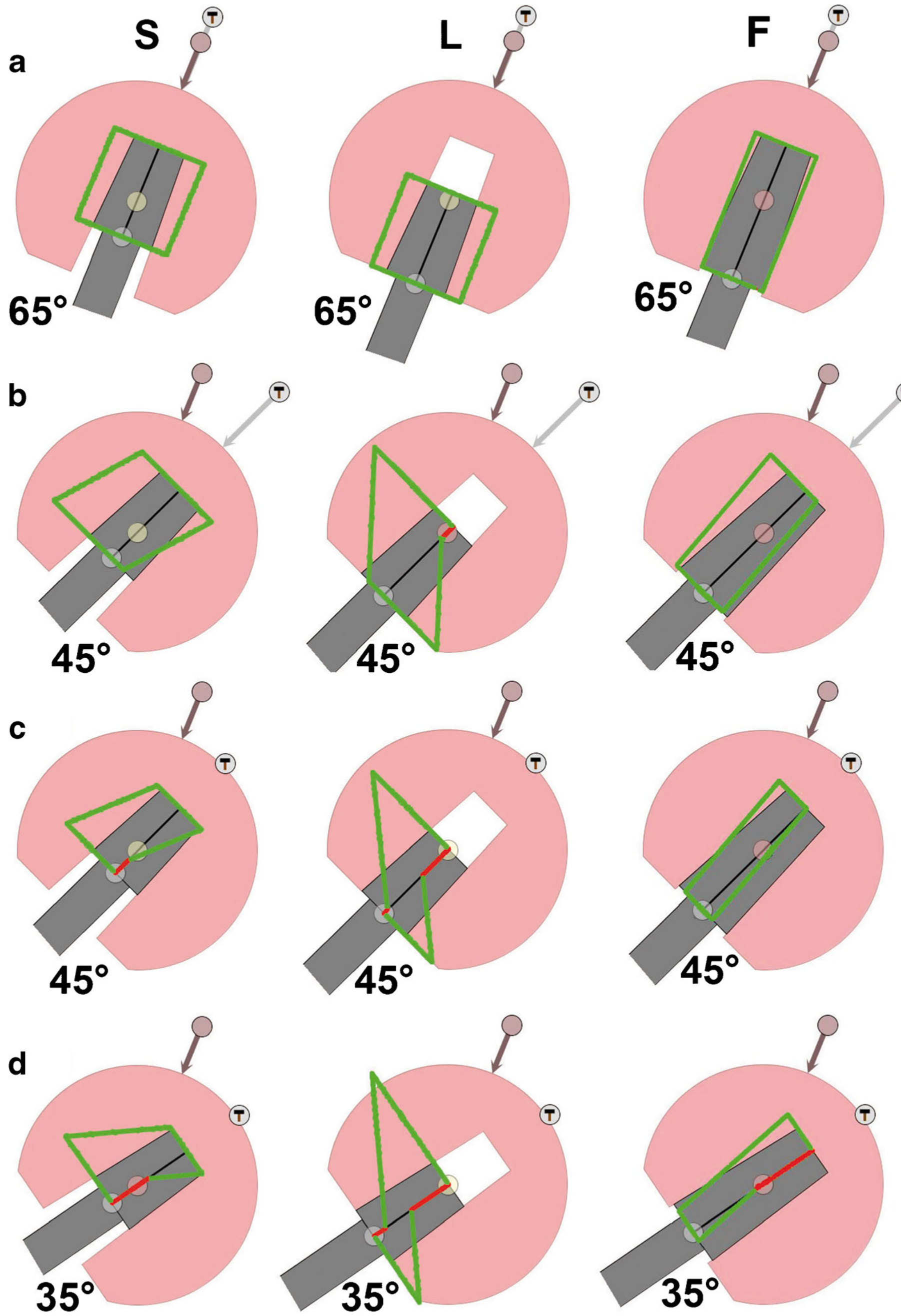


Fig. 3. Idealized radial stresses (*green*) at the taper interface between the female ball head and the male stem taper for short ("S" *left*) and long ("L" *middle*) heads and for a long taper ("F" *right*) in static balance with the applied forces. A 12/14 taper with an impaction force of 4000 N and a joint force of 2600 N is used to illustrate the influence of load direction, head length, and head impaction. **a** Impaction load (*grey*) and joint load (*brown*) aligned with the taper axis. **b** Taper axis 20° in varus from the joint load, leading to separation at the taper interface for the long head (*right*). **c** Situation (**b**) without an impaction force, leading to increased separation at the taper interface for both heads due to the overall reduced radial stresses. **d** Situation (**c**) with the taper axis in 30° varus from the joint load, leading to a further increase in separation at the taper interface.

designs can be safely combined [10, 49]. The solution again is simple: do not take any risks.

The choice of matching components is prerequisite and the assembly procedure is the next crucial step in achieving a good fixation of the ball head on the stem. Tapers are designed for clean and dry assembly conditions. Assembling them in a contaminated situation (blood, bone, water, fat) causes an increase in micro-motion during loading or a reduction in fracture strength of ceramic heads [26, 32, 37, 45, 53]. This is the reason why stem tapers should always be carefully cleaned, rinsed, and dried before assembly. Assembling them with insufficient force causes less firm fixation, with a risk of increased micro-motion during loading [21, 25, 42, 44]. Contact area and fixation strength increase linearly with impaction force [44, 52]. Larger heads require higher assembly forces since their higher joint friction moments must be withstood by the taper interface [6].

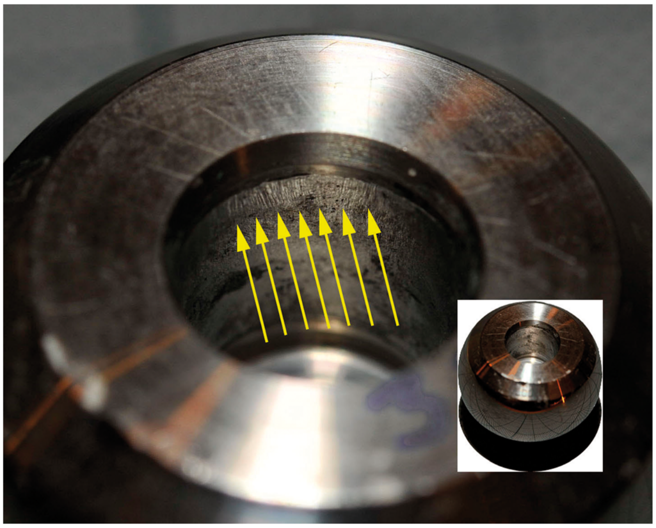


Fig. 4. Massive fretting marks and material loss on the female taper of a +5 and 36-mm diameter CoCr head combined with a titanium alloy V40 taper revised due to adverse responses to metal debris.

Discussion

Total hip arthroplasty has been called the "Operation of the twentieth century" and modular implant systems have contributed greatly to this success [34]. It is hypothesized in this review that the taper problems presently reported for bearing articulations involving polyethylene as bearing partner are mainly a result of the increase of mechanical loading (head size, offset, patient weight and activity, varus stems) and simultaneous reduction of loading capacity (taper length, taper diameter, softer alloys) combined with the underemphasized importance of contamination and proper assembly. Furthermore, even though it may not have been the reason for the revision [13, 39], evidence of corrosion of metal alloys will be found in most revision procedures due to the fluids in the human body, which contain water, dissolved oxygen, proteins as well as ions such as chloride and hydroxide, comprising an aggressive environment for metals in the human body. The important question is when does corrosion become a clinical problem? In order to answer this question, the methods used to quantitatively determine material loss at the taper interfaces need to be improved [9]. The qualitative scores presently used in most studies have proven to be useful, but they should not be used as a substitute for the measurement of material loss [18, 23]. Finally, only once we are able to reproduce the corrosion patterns observed clinically in the laboratory (not yet possible) will we be able to systematically identify the "most robust" taper design and the influences of the important parameters [36].

Clinical symptoms associated with an elevation in Co and Cr ion levels in blood or serum and a Co/Cr ratio of greater than 1.5 clearly point to a taper problem that needs be addressed [22, 28]. A critical level for the ion concentrations has not been established and probably varies between individuals. During revision, the male taper of titanium alloy stems should be thoroughly cleaned and inspected. Although the corrosion products are mostly observed on the male taper, they originate from the female surface and in most cases, it should be possible to retain the stem if there is no mechanical damage to it [28]. The use of a ceramic head

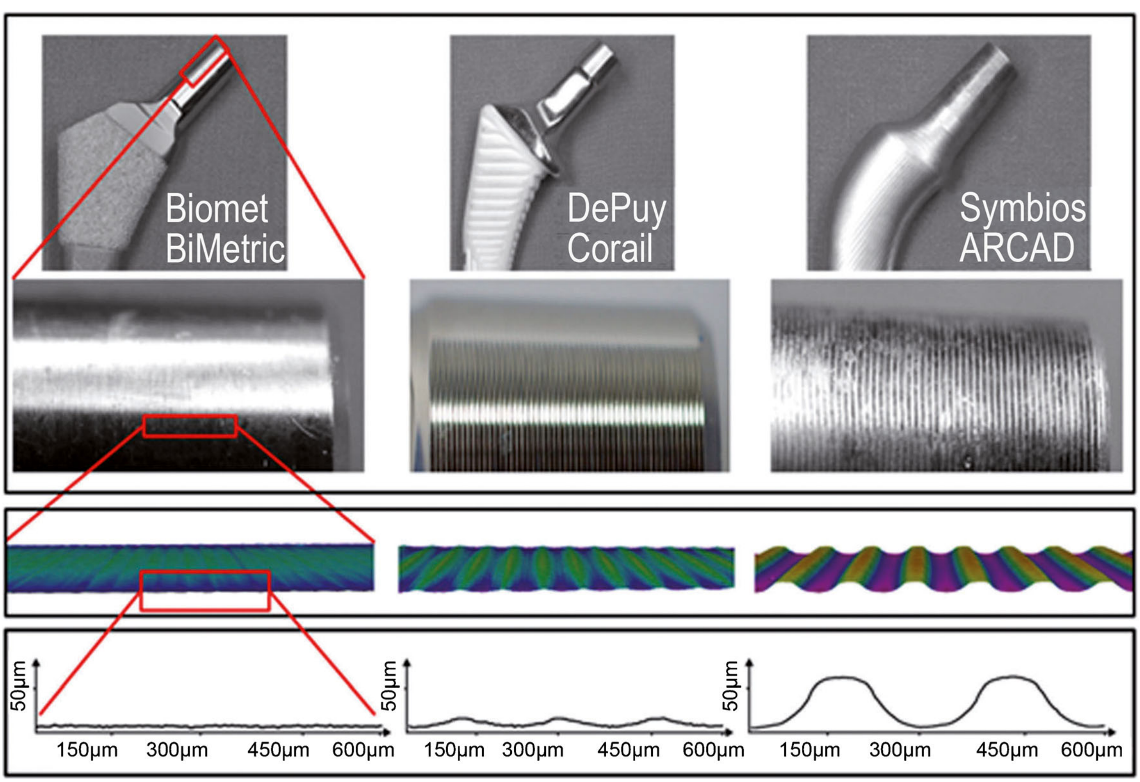


Fig. 5. Taper surface morphology for three different manufacturers illustrating surface roughness and ridges.

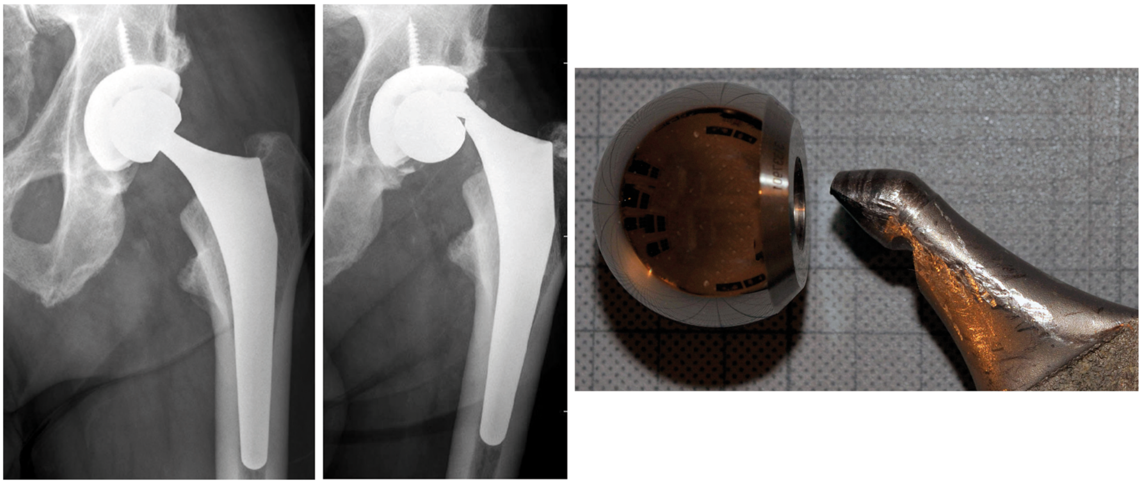


Fig. 6. Dislocation of the male stem taper from the female ball head taper combined with major CoCr wear of the female ball head taper and Ti alloy wear on the male stem taper after 9 years in an active male patient without clinical problems prior to disassociation.

with a Ti alloy adapter sleeve is advocated by most studies [28]. The surgeon should be aware that the Ti alloy adapters are also manufacturer specific and that they should not be mixed between companies.

Complex systems such as the patient-surgeon-implant system are intrinsically hazardous [11]. A small change (or, as in this case, changes of several factors) can lead to a strong increase in formerly only anecdotally reported problems. Manufacturers, patients, surgeons, and lawyers tend to look for the single "root cause," negating the multi-factorial nature of the problem.

The combined effect of some of the factors discussed in this review can best be illustrated with a clinical example (Fig. 6). Dislocation of the male stem taper from the female ball head taper occurred after 9 years in an active male patient without clinical problems prior to disassociation. X-rays and analysis of the revised components revealed major CoCr ball head wear on the female ball head taper and catastrophic Ti wear of the male stem taper. The patient did not have any metal debris-related symptoms even though the concentrations of Co, Cr, and Ti must have been elevated (they were not measured). What caused the implant failure? From a biomechanical point of view, speculation with respect to the underlying process (the "how") can be attempted. Excessive micro-motion between ball head and stem taper led to initiation of fretting and crevice corrosion, causing material loss on the female ball head taper, increasing the taper diameter inside the head. This led to a loss of the press fit between the ball head and stem taper and consecutive "bottoming out" of the stem (contact of the tip of the stem taper with the bottom of the female head taper). The head then started to spin on the taper, abrading the Ti stem neck at its contact point medially due to the bending loading of the joint force. This caused the head to go into increasing varus. Once the stem taper was worn down sufficiently, disassociation took place. We suggest that this is how the dissociation occurred. The question regarding the "why did this happen?" is much more difficult. Was it the high activity level of the patient? The soft titanium used for the stem (one of the most popular successful uncemented stems in the UK)? The large head diameter (36 mm is large)? The offset? Contamination during assembly? Insufficient assembly force? A little bit of all of these factors? Post "accident" analysis cannot reveal the reason(s). What is known is that simultaneously reducing the mechanical loading of the taper interface (e.g., smaller heads) and increasing its load capacity (e.g., using larger tapers) while respecting the importance of cleaning, drying, and assembly (even through small incisions) will reduce the risk of taper corrosion immediately, even if not all contributing factors are understood fully.

Compliance with Ethical Standards

Conflict of Interest: Dennis Bünte, Dipl.-Ing., and Julian Gührs, MSc have declared that they have no conflict of interest. Michael Morlock, PhD, reports personal fees from DePuy Synthes, Zimmer, Ceramtec, Smith & Nephew, Aesculap and Corin; grants from DePuy Synthes and Ceramtec outside the work. Nicholas Bishop, PhD, reports personal fees from DePuy Synthes outside the work.

Human/Animal Rights: This article does not contain any studies with human or animal subjects performed by the any of the authors.

Informed Consent: N/A

Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

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