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# Taper corrosion: a complication of total hip arthroplasty

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- The focus on taper corrosion in modular hip arthroplasty increased around 2007 as a result of clinical problems with large-head metal-on-metal (MoM) bearings on standard stems. Corrosion problems with bi-modular primary hip stems focused attention on this issue even more.
- Factors increasing the risk of taper corrosion were identified in laboratory and retrieval studies: stiffness of the stem neck, taper diameter and design, head diameter, offset, assembly force, head and stem material and loading.
- The high variability of the occurrence of corrosion in the clinical application highlights its multi-factorial nature, identifying the implantation procedure and patient-related factors as important additional factors for taper corrosion.
- Discontinuing the use of MoM has reduced the revisions due to metal-related pathologies dramatically from 49.7% (MoM > 32 mm), over 9.2% (MoM ⩽ 32 mm) to 0.8% (excluding all MoM).
- Further reduction can be achieved by omitting less stiff Ti-alloys and large metal heads (36 mm and above) against polyethylene (PE).
- Standardized taper assembly of smaller and ceramic heads will reduce the clinical occurrence of taper corrosion even further. If 36 mm heads are clinically indicated, only ceramic heads should be used.
- Taper-related problems will not comprise a major clinical problem anymore if the mentioned factors are respected.


**Keywords:** taper; design; corrosion; contamination; assembly; loading; metal

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Corrosion at modular taper junctions has been a known phenomenon for the last 30 years. Interestingly the first paper addressing the issue came to the conclusion that 'there should be no occurrence of long-term in-vivo fretting corrosion' of heads made from Cobald-Chromium-Alloy or Ti6Al4V stems.[1] Today it is well known that such a general statement was not justified based on pre-clinical testing alone, which is always a drastic simplification of in-vivo loading and environment. A PubMed literature search (13 July 2020) with the search terms '(taper OR trunnion) AND (hip) AND (corrosion)' yielded 350 relevant hits, demonstrating the continuing interest in this topic. The reported studies describe clinical observations based on explant analyses from single cases or case series or the results of laboratory testing, systematically investigating the influence of the parameters derived from the clinical observations on the risk of taper corrosion. The main findings of these reports are summarized in this review, but the goal is not to add another review article to this topic but rather to focus on the question: How big is the taper corrosion problem currently in a representative setting in Germany after the removal of the most endangered designs from the market? The second goal is to formulate measures based on this analysis to further reduce the problem in the future.

## History

### *Design*

The original Morse taper was invented by Stephen Morse in the 1860s for machine tool operators, allowing them to install or remove tool bits quick and easily, and is still used in contemporary machines. It had a relatively small angle of 2.9° resulting in a steep taper angle.[2] The Morse taper

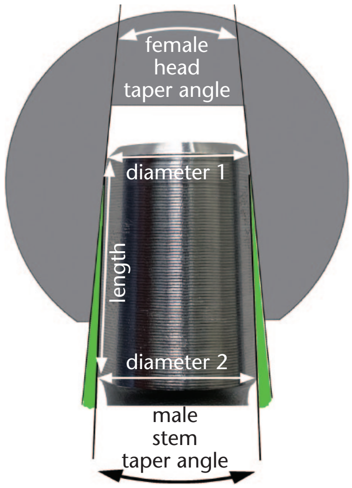


**Fig. 1** Definition of the head-stem taper connection. The male stem taper geometry is defined by the proximal and distal diameters and its length. The ‘12/14’ taper is defined with a proximal diameter of 12 mm, a distal diameter of 14 mm and a length of 20 mm, resulting in a male stem taper angle of 5.725° or 5°43’30” (the same angle as in the original ‘14/16’ taper). The female taper angle of ceramic heads is always by 1’ to 6’ larger, in order to achieve initial proximal engagement between female and male taper.[6] Most metal heads are designed similarly but some are manufactured with the same nominal female taper angle as the stem. The true contact length depends on the assembly force and the taper angle difference (indicated in green).[85] All these values are not standardized and vary between manufacturers.[86]

was introduced in Total Hip Arthroplasty (THA) at the end of the 1970s for the assembly of ceramic heads to metal stems after problems with the fixation strength of ceramic heads fixed by glueing or screwing.[3] They became widely popular around 1985 to allow the combination of different materials in general, i.e. also cobalt–chromium heads on titanium-alloy stems, and to adjust combined offset and leg length intraoperatively. The original taper dimension in THA was ‘14/16’, which refers to a truncated cone of 20 mm length with diameters of 14 mm and 16 mm at either end (resulting in the abovementioned taper angle of 5.725°). This taper angle had been shown to be favourable for higher fracture loads of ceramic heads.[4] In the 1990s, the taper dimensions were reduced to smaller diameters such as 12/14, 11/13 or even 9/10 and new denotations such as C-taper, Type-1 taper or V40 taper were introduced. A reduction in taper length occurred concomitantly (from 20 mm to below 10 mm).[5] All these changes were made to increase the possible range of motion of the joint with the use of small ball heads (32 mm diameter and below). The downside of all these changes was a reduction of taper contact area and taper bending stiffness. Today in Europe the so-called ‘12/14 taper’ or ‘Euro taper’ is the most frequently used design (with a similar angle as the original ‘14/16 taper’, Fig. 1).

There are some important basic facts about metal tapers, which help to understand the taper problems observed:

(1) There is not now and never has been a standard defining specific taper dimension. As a consequence, tapers between (and even within) manufacturers vary. Even so, they might be named similarly.
(2) Tapers were designed for and perform best under torsional loading around the taper axis and poorly under bending loading (as in high offset stems, long heads, large heads, and especially for modular necks and revision stems).

*Clinical situation – Metal-on-metal bearings*

Since dislocation was one of the most frequent revision reasons, larger heads were used more frequently, starting around 2004, to reduce the dislocation risk.[6] Since larger heads generate more wear against polyethylene (PE), metal-on-metal (MoM) hard-on-hard articulations started to become popular to enable larger head sizes. Opposite to PE bearings, the amount of wear in MoM bearings decreases with head size – as long as they are lubricated properly. This was supported by good results for hip resurfacing arthroplasty.[7] In unfavourable lubrication situations, however, MoM bearings can generate high friction, which in turn increases the bending and torsion torque at the taper interface.

Clinically, large MoM bearings on standard hip stems did not perform well from the beginning. In 2009, a prospective study comparing hip resurfacing to large MoM bearings for a similar design caused great concern, since the metal ion concentrations in the MoM group were found to be elevated.[8] Since the taper junction was the only difference between the two groups in this study, the taper problem was ‘identified’. Prior to this publication, the taper interface was not seen as a critical factor since the focus in MoM was solely on wear and friction of these bearings. As a consequence, no distinction between hip resurfacing and large MoM was made.[9–11] In the 2009 annual report of the National Joint Registries of England and Wales (NJR), the results of resurfacing and large-head MoM are consequently reported together.[12] In 2010, when the problems with large-head MoM prostheses were starting to become evident, the results were reported separately.[6] The scientific interest in this topic, as reflected in the number of publications, started to rise right around this time (Fig. 2).

Initially one implant design was mainly held responsible for the taper corrosion problems observed (the Articular Surface Replacement (ASR) design by DePuy).[13,14] This device was recalled in 2010, which, however, did not resolve the problem. It quickly became clear that the whole ‘category’ of large-head MoM exhibited a much

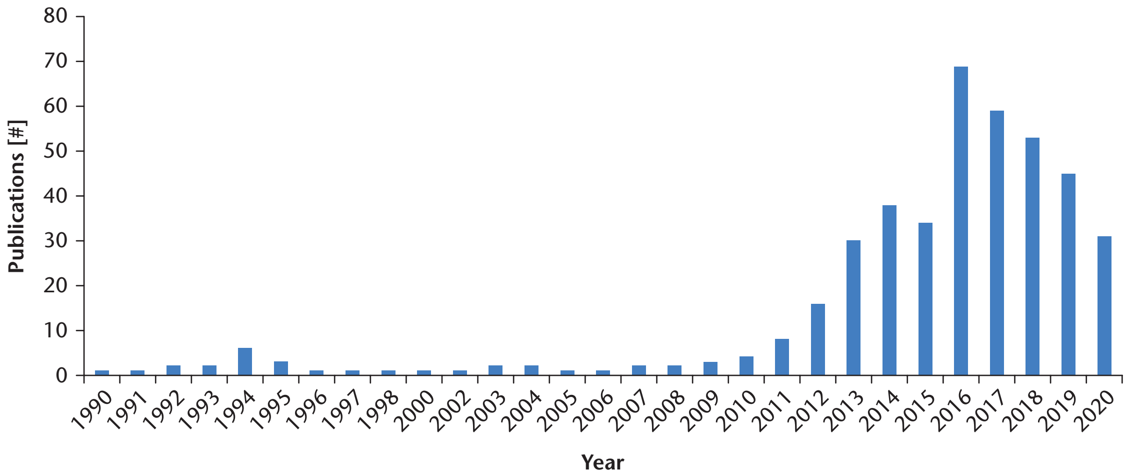


**Fig. 2** Number of peer-reviewed journal publications for the search terms '(taper OR trunnion) AND hip AND corrosion' in PubMed. The number of publications started to increase from the few anecdotal reports published before 2009 and peaked in 2016 with continuing high interest since.

higher risk of taper corrosion in comparison with smaller bearings against PE. The great public interest in the corrosion issue is due to the fact that the metal debris produced by wear or corrosion can be directly associated with clinical symptoms leading to revision, which was first reported for resurfacing[15,16] and soon after for large MoM bearings.[17,18] In MoM bearings the material loss from the cup bearing surface and the female taper were shown to demonstrate the greatest material loss.[19]

Stem taper fracture as the worst clinical endpoint of taper corrosion has been observed in only one particular MoM design using a Ti-alloy adapter sleeve connector with a Ti-alloy stem (Fig. 3). In this design a high frequency of cold welding between stem and adapter was also observed.[20]

The risk of taper corrosion in large MoM THAs was ultimately taken up politically by the European Commission with the establishment of a Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) working group investigating 'The safety of Metal-on-Metal joint replacements with a particular focus on hip implants'. The consensus of this working group, advising against the use of large MoM bearings, was implemented shortly afterwards.[21] Discontinuing the use of MoM has reduced the revisions due to metal-related pathologies dramatically from 49.7% (MoM $>$ 32 mm), over 9.2% (MoM $\leqslant$ 32 mm) to 0.8% (excluding all MoM).[22,23]. However, the discontinuation of large MoM bearings did not completely eliminate the taper corrosion issue.

### *Clinical situation – bearings utilizing PE*

Just around the time that MoM THA was discontinued, several reports reporting taper corrosion with metal heads against PE were published and this continues today.[24,25] Catastrophic gross stem taper failures (GTF) due to corrosion and abrasive taper wear are the newest addition to the taper corrosion story.[26] Such failures are reported mostly for one particular stem design with a small V-40 taper made from a less stiff Ti-12Mo-6Zr-2Fe titanium-alloy (TMZF; Accolade I, Stryker, Mahwah, New Jersey, USA) in combination with heads made of Cobald-Chromium-Alloy (CoCr) of sizes of mostly 36 mm and above.[27–31]

## Factors influencing the occurrence of taper corrosion

Any modular connection involving metal alloys will show some corrosion if in contact with body fluids and exposed to micromotion.[32–34] Tapers were introduced in engineering for the transfer of loads applied along the taper axis. Loads applied off-axis – as is the normal situation for the head-stem taper connection in THA – together with joint friction moments, cause a bending load at the taper interface with non-symmetrical compressive radial ('hoop') stress distributions. This stress asymmetry results in micromotions or even a loss of contact during cyclic loading, leading to fretting and crevice corrosion (Fig. 4). The magnitude of micromotion at the taper interface is influenced by several factors, which can be categorized into three groups:

- design and material;
- assembly (surgeon factors);
- loading (patient factors).

### *Design and material*

Taper surface morphology (rough or smooth, long or short) has been shown to influence the amount of corrosion observed but the data are still insufficient to draw

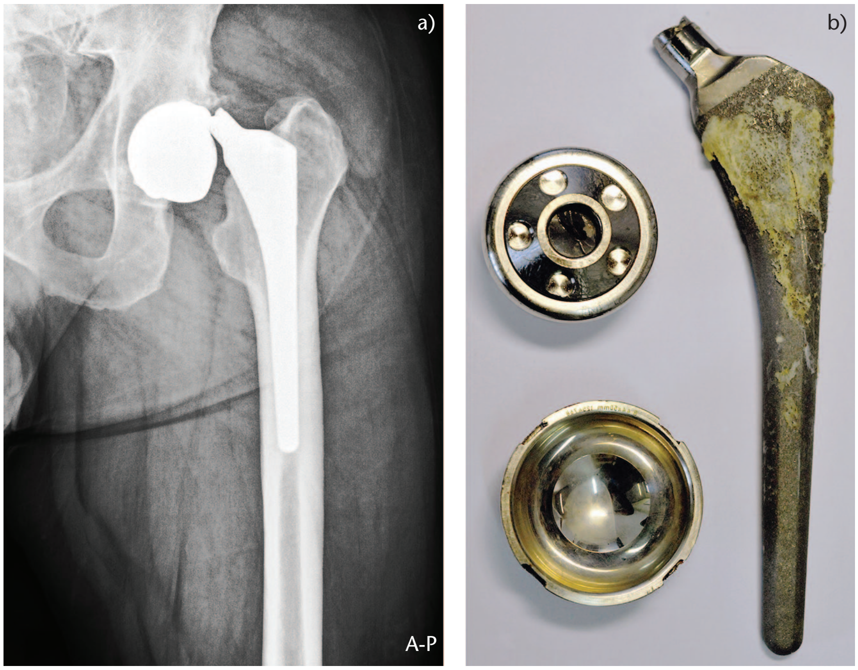


**Fig. 3** (a) X-ray of a stem taper fracture in a Ti-alloy primary stem with a large MoM bearing after four years in situ. This design utilizes a Ti-alloy adapter sleeve to assemble the CoCr-bearing surface to the stem. (b) The explanted components with the broken stem taper inside the adapter sleeve inside the head (courtesy H. Ettema, Isala).

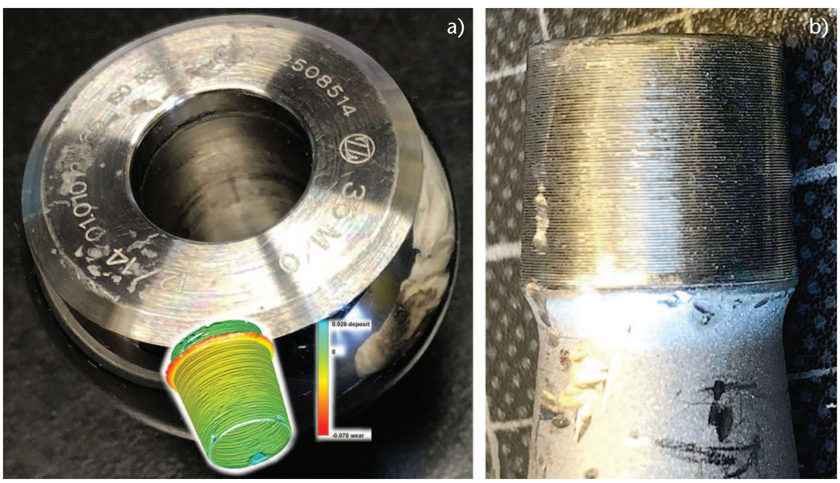


**Fig. 4** (a) Female head taper corrosion after seven years in situ. The overlay shows the depth of the female head taper wear (material loss 6.7 mm$^3$). (b) The male stem taper did not show signs of corrosion but slight marks from the revision surgery.

definite conclusions.[35–37] Even so it was shown early on that low neck stiffness is a contributing factor for corrosion,[32] changes in taper design over the last 20 years have led to even more flexible tapers,[38] which consequently show more corrosion.[39]

Long and large heads, varus stems and higher offset stems apply higher load to the taper interface and as such exhibit more fretting and corrosion.[40–47] Fracture of hip revision stems are a ‘good’ example to illustrate this (Fig. 5): Due to the long lever arm of the joint load to the stem–neck piece taper connection, the risk of micromovement with consecutive corrosion is clearly elevated, especially under unfavourable loading conditions, ultimately resulting in an elevated rate of taper fracture at the neck piece stem taper.[48] Similar arguments can explain the higher corrosion problems for dual taper hips.[49,50]

Finally, the frequency of metal debris-related revisions was shown to be greatly reduced when using ceramic heads,[51–53] especially in the combination with PE as an acetabular bearing partner.[54,55]

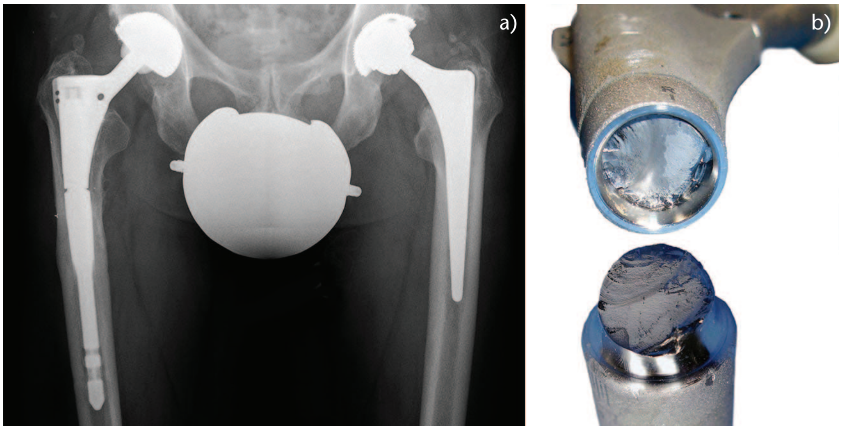


**Fig. 5** (a) X-ray after fracture of of a Ti-Ti Revision stem after seven years in situ (courtesy M. Rudert, Würzburg). (b) Fracture surfaces of the broken taper showing the typical split lines of a fatigue fracture.

In modular hemiarthroplasty, taper corrosion seems to play a much smaller role, however, a few cases have been reported.[56–59]

### *Alloy combinations*

Corrosion at Ti-alloy–Ti-alloy taper junctions is typically not recognized until catastrophic failure occurs as a result of the absence of a biological response to the Ti debris in most cases (i.e. fracture, Fig. 3, Fig. 5). In contrast, clinical failure of taper junctions between CoCr heads and Ti-alloy stems typically does not involve mechanical failure but is caused by the biological response to the Co and Cr debris, which is created in the corrosion process (Fig. 4).[34] It is important to realize that the male stem taper is usually not damaged in such an situation, even so it might look corroded due to the Co and Cr debris from the inside head taper. After careful cleaning it is possible in most cases to maintain the stem and put on a ceramic head with a Ti-alloy adapter sleeve.[54] Both CoCr heads and ceramic heads on CoCr stems show a very low material release.[60] The results for oxidized zirconium heads in comparison to CoCr heads are favourable but inconsistent.[51,61]

### *Assembly*

The assembly condition plays an important role in the strength of the taper connection.[62,63] Minimal invasive surgery with small incisions might indirectly also be associated with the frequency of taper corrosion due to the challenges in cleaning the taper and to apply appropriate assembly forces in taper direction. Tapers are designed for clean and dry assembly conditions. Assembling them in a contaminated situation (blood, bone, water, fat) causes an increase in micromotion during loading or a reduction in fracture strength of ceramic heads.[63–68] Contamination might also reduce secondary seating after implantation due to the component of the joint contact force directed into the direction of the taper axis.[69] This is the reason why stem tapers should always be carefully cleaned, rinsed and dried before assembly. Insufficient assembly force causes less firm fixation, with a risk of increased micromotion during loading.[70–72] Contact area and fixation strength increase linearly with impaction force.[71,73] Larger heads require even higher assembly forces since their higher joint friction moments must be withstood by the taper interface.[74]

### *Loading*

The loading magnitude and direction directly influences the micromotion at the taper interface.[75] A continuous increase in the obesity rates in most populations, reaching 42.4% in the US in 2017 to 2018,[76] has continuously increased the load on the taper interface,[77] especially in combination with larger head sizes, which is a common trend, especially in the US.[78] In the last few years a further aspect has been highlighted: the composition of the body fluids surrounding the taper junction. It could be shown that inflammatory conditions enhance the risk of corrosion of CoCr and Ti-alloys.[79,80]

Despite the influence of the mentioned parameters on the loading of the taper, corrosion has been shown for nearly all taper designs and implant configurations.[81]

## Present situation in Germany

In order to get an impression of the present magnitude of the taper corrosion problem in Germany, an observational study in cooperation with four of the leading German orthopaedic hospitals was performed (Charite Berlin, Endo-Klinik Hamburg, OCM Munich, Uni Greifswald). Intra-operative pictures of the male stem taper during revision surgeries, in planned cup revision surgeries, in which the stem was expected to be maintained, were taken. These qualitative pictures, in combination with the revision reason specified in the surgical report, were used for the classification of the revision reason in 100 cases.

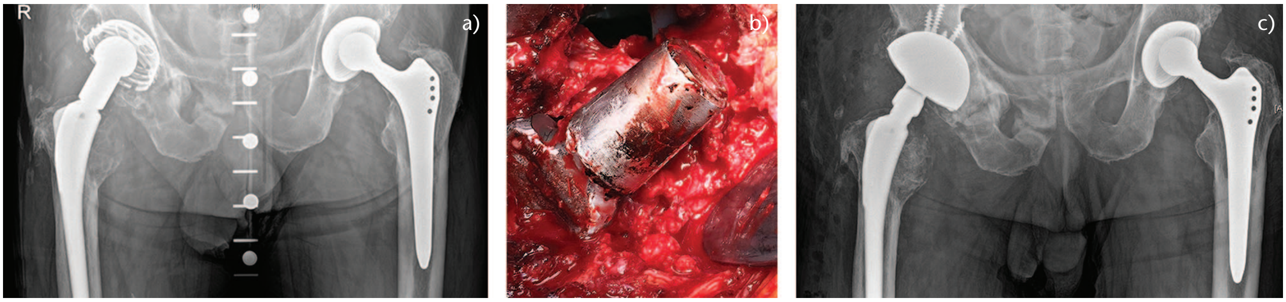


**Fig. 6** (a) X-ray of a male patient (76 years) prior the 4th isolated right cup revision in 2019 after original stem implantation with a 32 mm metal XXXL head in 1984. (b) The stem taper showed only light corrosion and minor damage from the multiple revision surgeries. (c) X-ray after the revision with a 36 mm ceramic option XXXL head on the original stem.

Not all revision cases in the respective hospitals were documented due to time limitations in the surgical routine. As a consequence, a rather arbitrary and random selection was achieved. Head taper corrosion was the reason for revision in 3% of the cases: one case with corrosion of the female head taper in a large MoM bearing (50 mm) and two cases with corrosion of the female head taper in 36 mm metal heads against PE (Fig. 4). In one case of corrosion at the neck taper of a bi-modular stem design, the stem had to be removed (1% of the cases). This confirms the general perception in Germany that taper corrosion problems predominantly occur for designs already identified at risk, which were not frequently used in Germany in the past. This is also reflected by the fact that metal debris-related revision is not even listed as a revision reason in the Endoprothesen Register Deutschland (EPRD) German Arthroplasty Report 2019.[82]

## How to minimize future taper problems in the patient

THA is frequently referred to as the ‘Operation of the 20th century’ and modular implant systems have contributed greatly to this success.[83] In this review, the history of the evolution of taper design together with the evidence on the factors, which are thought to influence the frequency of clinically observed taper corrosion, are summarized. It is impressive how much research has been conducted and still is conducted on this issue (Fig. 2). There is wide agreement that taper corrosion is a multi-factorial phenomenon influenced by the three factor groups addressed in this review: mechanical loading (head size, offset, friction, patient weight and activity, geometrical configuration), the reduction of loading capacity due to recent design changes (taper length, taper diameter, softer alloys, taper surface morphology) and the rather underemphasized importance of contamination and proper assembly. Furthermore, corrosion of metal alloys always occurs in the human body due to the aggressive environment, but does not necessarily become a clinical problem as long as the amount of corrosion is small.[34,42,84]

The final and most important question concerns the further reduction of the frequency of taper corrosion problems. Even so, not all aspects of the corrosion mechanism in-vivo are known yet. There is more than enough evidence that respecting only one of the decisive factors alone will not solve the taper corrosion problem but that all factors have to be addressed simultaneously. The suggestions given below summarize the required measures:

1. The use of 36 mm metal heads should only be for a good clinical reason and if it can be ascertained that they are assembled properly to a clean taper. The safer option is the use of a 36 mm ceramic head.
2. A reduction in head size reduces the occurrence of taper corrosion.
3. Stems made from less stiff metal alloys in combination with small tapers should be omitted. Small tapers, especially in combination with large heads, should be used carefully.
4. Large offsets, especially in combination with long heads, carry a higher risk for taper corrosion.
5. The use of ceramic heads reduces the taper corrosion risk significantly.
6. Careful and proper cleaning and assembly reduces the risk of taper corrosion in all configurations.

Taper corrosion is a complication that can occur in any THA, independent of design and head size, as long as stems are made from metallic alloys.[81] Respecting the mentioned measures will further reduce the magnitude of the problem, which was already greatly reduced by the elimination of MoM THA bearings. The very low observed rate of taper corrosion in Germany is probably mostly attributed to the long-term education of the proper use of ceramic heads (‘clean and impact’) and the traditional use of smaller head diameters in metal heads:[54] In 2019, 88% of all implanted heads were ceramic and the dominant head size was 32 mm (54%).[82] If properly assembled and not exposed to excessive loading, metal heads can also provide very good long-time survival in the patient, even in adverse loading conditions if assembled properly (Fig. 6), but the diameter of the heads should not exceed 32 mm.

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