Review Article

Trunnions and Modularity in Total Hip Arthroplasty: A Historical Review With Current Clinical Implications

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ABSTRACT

Trunnion in total hip arthroplasty refers to the interface between the neck of a femoral stem and the femoral head. Clinical complications arising from damage to this junction, whether it be due to mechanical wear, corrosion, or a combination, are referred to as mechanically assisted crevice corrosion (MACC), also commonly known as trunnionosis. With the use of modular hip prostheses, which help customize offset and leg length to an individual patient's anatomy, the incidence of MACC and revision due to MACC has increased in recent years. Although the cause of MACC is multifactorial, with patient factors and technique factors contributing to this condition, taper design and geometry, metallurgical properties of implants, and size mismatch of the bearing couple are some of the implant factors that have also been implicated in this clinical phenomenon. Understanding the history of taper design and geometry, the track record of older implants, and the rationale behind the development of current prostheses can help surgeons choose the right implants for their patients and accurately assess the pros and cons of new implants being introduced to the market each year.

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Charnley[1] became the father of the modern total hip arthroplasty (THA) when he introduced his low-friction design in 1961. He used acrylic cement to fix metal to live bone, polyethylene as a bearing surface, and monoblock femoral implant with a small head for low frictional torque. Introduction of modularity allowed the separation of Charnley monoblock femoral implant into the femoral stem and femoral head. This allowed fine-tuning of the femoral offset and leg length independent of the femoral stem size, thus facilitating customization of the implant to the individual's anatomy.[2] However, modularity comes with its own risks and disadvantages, and understanding these can help the orthopaedic surgeon decrease the risk of complications after THA.

Need for Modularity

The original hip prostheses by Charnley consisted of a cemented metallic femoral monoblock stem and a polytetrafluoroethylene acetabular shell. Although this combination results in a low-friction assembly, this couple led to notable wear and osteolysis in the short term, and Charnley switched to polyethylene. Although polyethylene had better performance, notable periprosthetic osteolysis was still observed because of mechanical wear resulting from a small metal head articulating with a large, first-generation polyethylene shell.[3] Ceramics such as alumina and zirconia were introduced in the 1970s as more suitable materials for femoral heads than metal because of their lower wear rate and better tribological properties when coupled with polyethylene shells.[4,5] However, because of the low tensile strength and high brittleness of ceramics, hip stems could not be manufactured from alumina. Therefore, modularity at the femoral head and neck junction was first introduced to overcome this obstacle.

Early methods of implantation of these ceramic heads, such as gluing or screwing, onto femoral stems led to unacceptably high implant failure rate because of femoral head dissociation or fracture.[6] The glue used to connect the ceramic head to the trunnion of the femoral stem was made of epoxy resin, which would degrade and lead to implant loosening and high wear at this junction.[6] The adoption of the Morse taper in orthopaedics in the 1970s solved these fixation issues and led to another leap in the technical advancement of THA.

Taper Design and Mechanical Wear

Stephen A. Morse, an entrepreneurial mechanic, invented the Morse taper in 1864 when he developed a technique to join two rotating machine parts.[7] The principle of the Morse taper is that of a cone in a cone—the trunnion (male part) and the bore (female part) are uniformly tapered such that when the bore is impacted onto the trunnion, there is interference fit between the two implants (Figure 1). The Morse taper technology jumped from metal cutting tools to orthopaedic surgery when German researchers adopted this assembly technique for fixation of ceramic heads on femoral stems.[8]

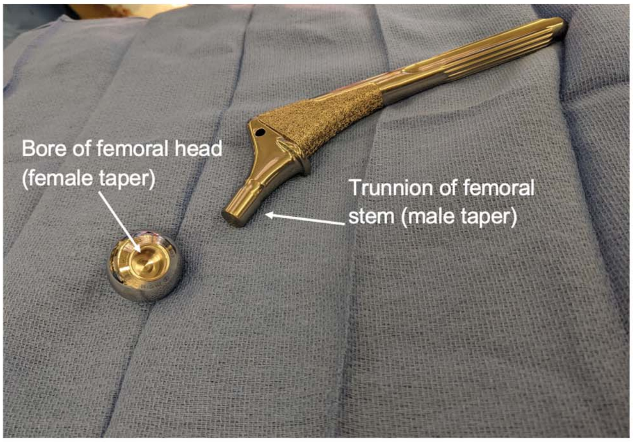
Although the original taper angle defined by Stephen Morse was 2° 50′, the taper angles used in arthroplasty range from 5° to 18° (Figure 2), and the Morse taper in orthopaedic surgery has become a generic term referring to any taper design that allows the reliable joining of modular implants.[7]

Since the advent of the Morse taper in arthroplasty, a number of different taper designs and geometries have been developed. The original taper dimension in THA was 14/16 and referred to a trunnion with a proximal diameter of 14 mm and a distal diameter of 16 mm with a taper length of 20 mm, resulting in a taper angle of 5° 43′ 30″. To accommodate smaller femoral heads, there was a shift toward smaller taper dimensions—12/14, 11/13, and 9/10—and a concomitant reduction in taper length from 20 to 10 mm in the 1990s. New iterations of tapers also included a C-TAPER (Osteonics), which was based on the 12/14 taper with a taper angle of 5° 40′; a V40 taper (Stryker Howmedica Osteonics), which had 8% less taper length with a taper angle of 5° 40′; and a type-1 taper (Biomet), which had a taper angle of 4° with a distal diameter of 12 mm.[9,10] An extensive, but not exhaustive, list of the common tapers currently in use has been provided in Supplemental Table 1, http://links.lww.com/JAAOS/A876.[11]

This general move by the implant industry toward smaller tapers had unforeseen consequences—reduction of taper contact area and bending stiffness and increased risk of fracture. Tapers, from a design standpoint, can withstand torsional loads very well and bending loads very poorly. Thus, using small tapers such as a V40 taper under high bending loads—that is, high offset stems, long heads, large heads, and obese patients—can lead to fretting corrosion of the taper and, in extreme cases, trunnion fracture.[12] Furthermore, the flexural rigidity of the taper has been inversely related to fretting damage, with more rigid tapers such as the 12/14 taper and C-TAPER having less stem fretting than the more flexible tapers such as the V40 and type I tapers.[13] Contrarily, contact length has been positively correlated with stem fretting.[13] This is partly explained by the fact that shorter trunnions, which have more contact length but sit entirely within the bore of the femoral head, may experience edge loading at the base and thus increased local stresses that can cause damage to the taper.[14] This situation is worsened by the recent push toward larger femoral head sizes with no compensatory modification to morphology of the trunnion. Although this increased head-neck ratio has the potential to decrease dislocation risk, it also comes with a higher risk of trunnion wear because of the increased horizontal lever arm.[14,15] Furthermore, the effect of these variables—taper size, flexural rigidity, contact length, and head size—on stem fretting is amplified when the trunnion is mated to metal heads.[16]

Other taper design characteristics that can affect implant longevity are surface finish and topography. Taper surface profiles can be classified into four categories based

Figure 1



Photograph showing the bore of a cobalt-chromium-molybdenum femoral head and the trunnion of a VerSys fiber metal midcoat stem by Zimmer Biomet.

on the surface finish (smooth vs threaded), topography (symmetric vs asymmetric peaks and valleys), and contact ratio (high vs low).[17] Type 1 tapers have a smooth surface profile (eg, Hipstar stem by Stryker), type 2 tapers have a rough but symmetric surface profile (eg, LINK stem by Waldemar), type 3 tapers have a rough and asymmetric surface profile with low contact ratio (eg, Bicontact S by Aesculap), and type 4 tapers have a rough and asymmetric surface profile with high contact ratio (eg, Fitmore by Zimmer).[17] Although no single type of taper is superior to other types, knowing the surface profiles of the different stem tapers can help the surgeon pair the trunnion with the right femoral head made of compatible material and taper tolerance. For instance, the rough surface profile of a taper is usually machined onto the trunnion with a lathe to accommodate ceramic heads. The topography can be adjusted by the manufacturer by varying the rotation speed, cutting tool, cutting speed, and feed rate on the lathe. This thread-like topography of the trunnion is aimed to create deformation within the surface of the ceramic head during head fixation to increase contact ratio but may leave imprints on metal heads, which can lead to crevice corrosion.[14] Thus, metal heads may be more compatible with type 1 tapers with a smooth finish than the other taper types that have rough surface profiles.

There is not only a notable variation of taper sizes and geometries among hip prostheses but also notable differences in machining tolerances of the same taper size among the different implant companies. Mueller at al[17] showed that stem taper length varied markedly among the different 12/14 tapers, with Corail (DePuy, Raynham, MA) having the shortest taper length and Bicontact S (Aesculap, Melsungen, Germany) having the longest (for a difference of 3.5 mm).[17] Furthermore, a variation of 0.1° was found in the taper angle among the different manufacturers, with Hipstar (Stryker) having the lowest value and SL-PLUS (Smith and Nephew) having the highest.[17] Parekh et al[18] showed that angular mismatch greater than 0.075° can lead to increased micromotion and corrosion at the taper junction. Thus, mixing and matching the femoral heads and trunnions, even if they are quoted to be the same taper type (ie, "12/14"), is not recommended because of the varying manufacturing tolerances among the different implant companies.

Material Properties and Corrosion

Mechanical wear and corrosion, a chemical activity referring to destruction of metals because of oxidation, are intricately linked in arthroplasty. Material properties of implants used in hip arthroplasty play an important role in the pathological processes leading to mechanically assisted crevice corrosion (MACC).

Femoral stems are made of either titanium (Ti-6Al-4V) or cobalt-chromium-molybdenum (CoCr) alloys, which form a surface oxide layer through a process called self-passivation in oxidative environments.[19] These passive radiographs, which act as barriers against corrosion, are disrupted when micromotion occurs between two tightly fitting surfaces, such as the bore of the femoral head and trunnion. When the oxide layer is disrupted, the metal becomes vulnerable to corrosion, and the ability to re-passivate is depleted with repeated cycles of disruption.

Figure 2

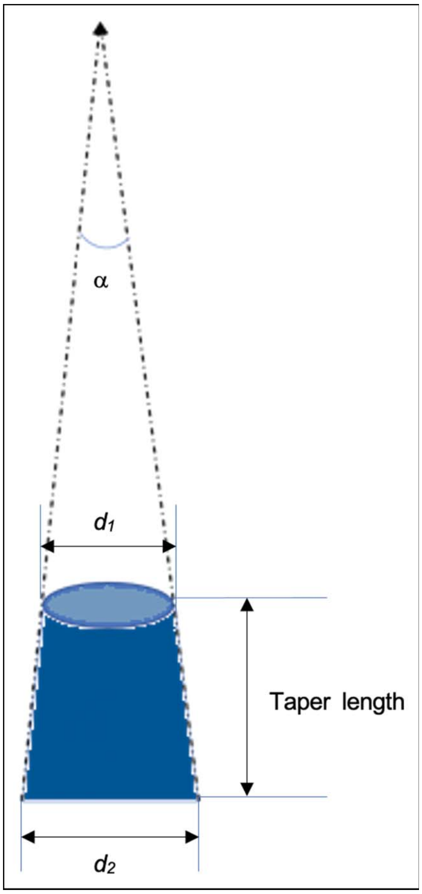


Illustration showing that α is the taper angle. d_1 and d_2 refer to the proximal and distal diameter of the trunnion (male taper), respectively. Taper length is the distance between proximal and distal diameters of the tapered portion of the trunnion. The female (bore in the femoral head) taper angle in ceramic heads is generally larger than the taper angle of the trunnion by 1′ to 6′ to accommodate initial proximal engagement between male and female tapers. Metal heads have a female taper angle similar to the taper angle of the trunnion because of the increased ductility of metal compared with ceramic, which comes with a risk of catastrophic fracture of the femoral head if hoop stresses exceed a certain threshold.

The wear and corrosion resulting from this mechanical disruption of the passive radiograph on metals is called fretting.[19]

Although fretting is the predominant and most common mode of damage to modular junctions, taper corrosion is often multifactorial. Other modes of trunnion damage include, but are not limited to, (a) crevice corrosion, where narrow crevices lead to low pH and thus higher oxidation states; (b) pitting corrosion, where local dissipation of oxide layer leads to formation of cavities surrounded by passivated surface; (c) galvanic corrosion, which occurs when dissimilar metals are in contact with each other in an oxidative environment; (d) intergranular corrosion, which occurs along the boundary of grains in metals; (e) etching corrosion, which is a uniform corrosion process of entire grains in metal; and (f) material transfer, where material from one surface is transferred to another because of adhesive wear.[20]

Some of the abovementioned modes of damage to the taper can be avoided if implants are chosen carefully, especially when assembling modular junctions consisting of dissimilar metals. The earliest femoral stems in hip arthroplasty were made of stainless steel, which was a cheap alloy that was resistant to corrosion and easy to produce.[21] However, the wear resistance of stainless steel was poor, and cobalt-chromium (CoCr) alloy stems were subsequently developed for their superior wear properties and biological inertness. Cobalt-chromium stems had a markedly higher elastic modulus than the cortical bone, which lead to stress shielding and bone resorption. This led to the development and use of titanium (Ti6Al4V) alloy stems, which had a lower modulus of elasticity than CoCr or stainless steel, better resistance to corrosion and creep, and higher biocompatibility. However, titanium stems came with their own drawbacks—they showed higher surface damage under axial loading.[22] In modern hip arthroplasty, both titanium and cobalt-chromium alloy stems are acceptable metals for femoral stems as long as the surgeon is aware of their individual advantages and disadvantages.

When coupling a particular stem with a femoral head, it is important to consider the metallurgical properties of each implant. Current evidence in the literature suggests that there is a higher rate of fretting and corrosion to the trunnion and head taper in mixed alloy couples (ie, CoCr head/titanium stem or titanium head/CoCr stem) compared with same-alloy pairing (ie, CoCr head/CoCr stem or titanium head/titanium stem). This is due to the increased risk of galvanic corrosion with dissimilar alloy pairing.[23] Furthermore, studies have shown that the least amount of fretting wear is observed with titanium-titanium couples compared with CoCr/CoCr or CoCr/titanium couples because of better interference fit by cold-welding in titanium-titanium interfaces.[15] However, titanium alloy is not a commonly used material for femoral heads because of its inferior wear properties and lower modulus of elasticity compared with CoCr or ceramic. Another factor affecting wear characteristics at the bore-trunnion interface is the coating process involved in the manufacturing of femoral stems. Press-fit stems are made porous with sintered beads or plasma spraying, which involves temperature increases that can alter the metallic structure of the stem distant from the site of coating, such as the trunnion.

This can affect the trunnion properties in unexpected ways. Thus, the risks and benefits of each femoral head-stem couple should be carefully considered when choosing implants during THA.

Mechanically Assisted Crevice Corrosion

MACC has been known to happen in at least four different modes: (1) adverse local tissue reaction (ALTR) related to taper damage and corrosion, (2) trunnion fracture, (3) dissociation of head and neck taper junction, and (4) fit mismatch between the femoral head taper and the stem taper.[24]

ALTR is a hypersensitivity reaction of the host to metallic debris released from taper damage, leading to an inflammatory response that is lymphocyte-dominated, hypertrophy of synovial tissue, and formation of a vasculitis-type lesion and pseudocapsule.[25] Risk factors of ALTR include, but are not limited to, (1) implant-related factors such as high head-neck ratio, dissimilar metal alloy couples, stems with lower flexural rigidity, and implant couples from different manufacturers; (2) surgical factors such as creating suboptimal loading conditions that require long neck extensions and lack of a proper impaction technique; and (3) patient-related factors such as high body mass index and increased cyclical loading of the joint.[25] This list of risk factors is not exhaustive and changes everyday based on new research being published.

Another implant-related factor that leads to higher risk of metallosis and consequent ALTR is dual modularity of the femoral stem. Separation of the femoral neck from the femoral stem was first introduced to improve biomechanics of the prosthetic joint. However, corrosion and wear at the neck-stem junction led to unforeseen complications, such as implant fractures and increased revision rates, typically around 7 years postoperatively.[26,27] The most common patient report is insidious onset of groin, thigh, or buttock pain after a certain length of pain-free postoperative period. Workup in such cases involves obtaining serum markers, metal ion levels, and advanced imaging such as an MRI scan.[28]

Not every patient who has an ALTR is symptomatic.[29] No research has been published to date elucidating why some patients have symptoms and some do not. Future studies are needed to determine the specific biologic and genetic factors that may play a role in patient predisposition to symptomatic ALTR.

Regardless of the presence of symptoms, once ALTR is diagnosed, it must be treated. Treatment of ALTR involves addressing the risk factors that contributed to taper damage and conducting either a one-implant or complete revision. The goals of surgery are to remove the source of metallic debris, débride necrotic tissue, and restore stability to the hip. If the source of ALTR is corrosion at the neck-stem junction of a dual modular stem, explant of the stem is recommended. If the patient has a well-fixed stem that is not dual modular, whether a new ceramic femoral head can be implanted onto a retained femoral stem depends on the amount of trunnion damage sustained and morbidity associated with revising the femoral stem. The taper design and geometry of the existing stem should also be taken into consideration when deciding whether to retain the stem,for instance, the 11/13 taper has a high corrosion score compared with other stem tapers and such short and narrow stem tapers may warrant stem revision because of their higher risk of localized stresses and recurrent corrosion.[30] We have developed a classification system to grade trunnion damage in Table 1. Figures 3 and 4 provide examples of different grades of trunnion damage. We have developed a management algorithm that provides guidelines on when to explant a femoral stem and when to retain it in Figure 5.

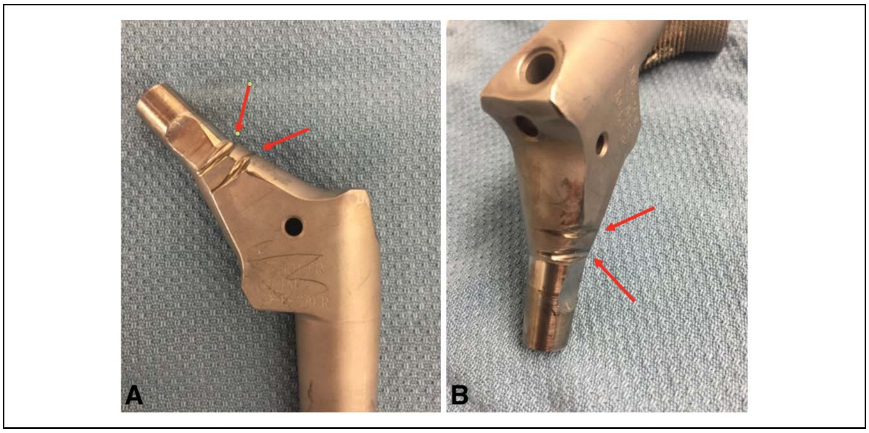
If the surgeon decides to retain the well-fixed stem based on the abovementioned algorithm, the ceramic head should be able to be securely mated to the existing trunnion because any mismatch or abnormal micromotion can lead to recurrence of wear and failure. When coupling the ceramic head to the existing trunnion, a titanium adapter sleeve is recommended to optimize taper fit and decrease material transfer because the sleeve provides a factory-finish surface in case of any surface defects on the in situ stem.[31,32] The one exception to this guideline occurs when treating ALTR in CoCr stem/CoCr head couples. In such cases, the ceramic head should be directly impacted onto the trunnion without an adapter sleeve because the titanium sleeve would introduce a mixed-metal couple, which increases the risk of metallosis. Impacting the ceramic head directly onto the used trunnion without a sleeve was previously thought to result in the rare complication of catastrophic head fracture, but recent studies have shown that adapter sleeves may not necessarily reduce this risk.[33] When impacting the femoral head onto the stem, an impaction force of 6 kN or greater is recommended to achieve improved pull-off strength and stability.[34] Multiple head strikes do not add stability.

1Trunnion fracture is a late-stage complication of taper damage where mechanically assisted fretting and crevice corrosion lead to gross metallosis and failure of the

Table 1. Classification System for Trunnion Damage and Treatment Guidelines

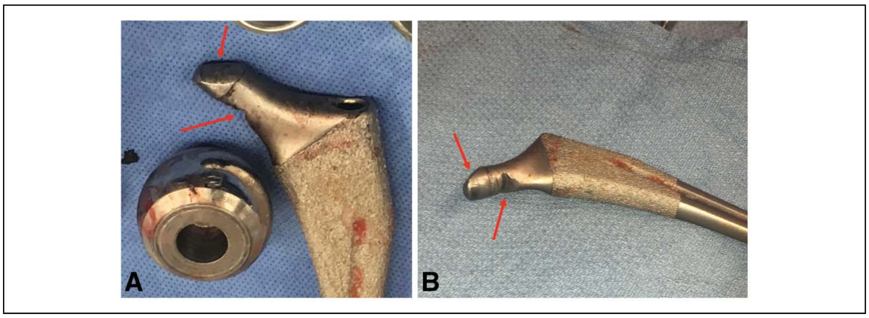
Grading	Diagnosis	Management
Grade 1	Corrosion products can be removed with a sponge	Retain the stem
Grade 2	Corrosion products can be removed with a scratch pa1d	Retain the stem
Grade 3	Evidence of pitting and crevicing on the trunnion	Explant the stem
Grade 4	Gross material loss	Explant the stem

Figure 3



A and **B**, Clinical images showing crevice corrosion of the femoral stem seen in grade three trunnion damage.

Figure 4



A and **B**, Clinical images showing material loss, rounding off of the trunnion, and crevice corrosion of the femoral stem seen in grade 4 trunnion damage.

stem. Although the risk factors of trunnion fracture are the same as those of ALTR, the most important contributing factor leading to catastrophic trunnion failure is femoral stress, as approximated by the offset distance (D) divided by the trunnion radius (R) cubed (D/R^3).[35] Any factor that increases this ratio, whether it be increased patient weight, increased total offset, or reduced trunnion diameter, leads to a decreased number of cycles before which crack initiation and propagation occurs. Another risk factor of gross trunnion failure is poor implant design. Stryker) LFIT Anatomic CoCr V40 femoral heads on Accolade 1 stems were recalled in 2016 because of gross trunnion failure resulting in catastrophic femoral neck fracture.[36] The mechanism of failure was thought to be a combination of material composition mismatch and MACC at the head-neck junction.[37] Once such a gross trunnion failure occurs, treatment involves femoral stem revision.

Dissociation of head and neck taper junction and fit mismatch are complications on the same spectrum of taper damage. Although dissociation of the femoral head can occur spontaneously or because of a traumatic event, the underlying cause is taper wear and corrosion leading to abnormal motion at the head-neck junction. Taper fit

Figure 5

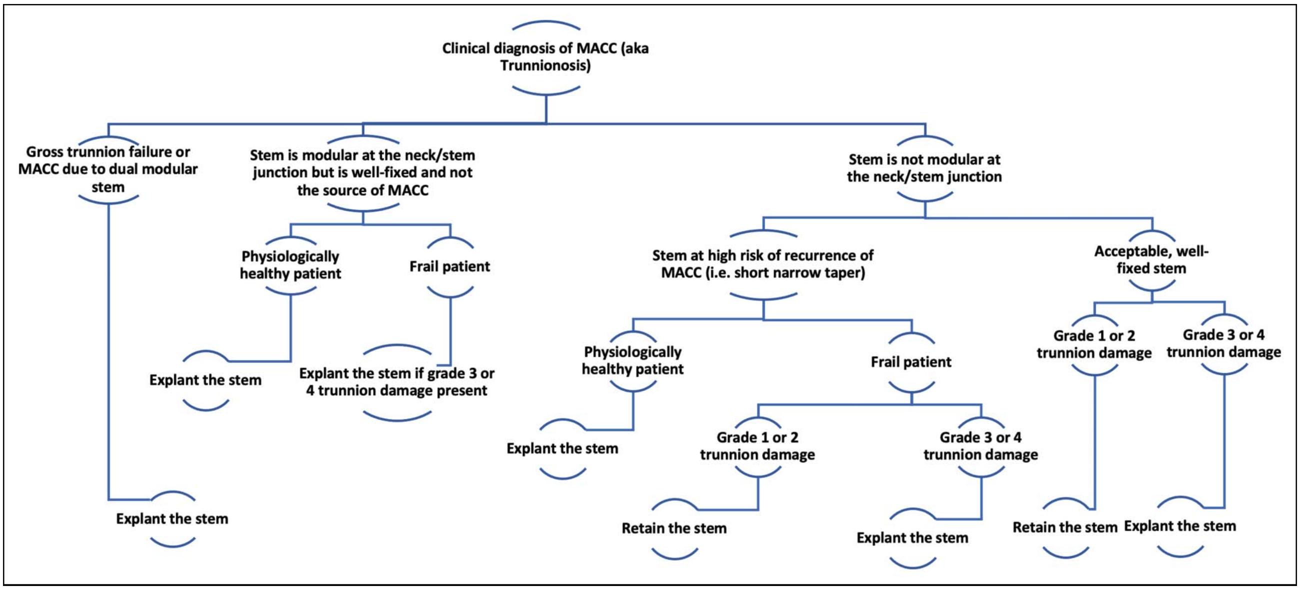


Diagram showing the management algorithm for mechanically assisted crevice corrosion (MACC).

mismatch between the head and the neck can lead to metallosis and fracture or ALTR in metal heads but can have more catastrophic consequences in ceramic heads. Taper mismatch between the trunnion and the bore of the femoral head can reduce fracture force of a ceramic head to less than half of its manufactured value, leading to catastrophic fracture of the ceramic head.[38] Furthermore, the effect of taper mismatch is multiplied in obese patients. Therefore, caution must be exercised when mixing and matching ceramic heads from one manufacturer with stems from another manufacturer because fit mismatch between the head and the neck is not grossly visible intraoperatively and can seem as if a stable couple has been achieved after assembly. The only reasonable way to determine whether a fit mismatch exists is by scrutinizing the manufacturing tolerances and specifications of the intended implants of the head-neck couple before surgery and modifying the surgical plan accordingly.

Surgical Technique Pearls

The evidence presented so far naturally lends itself to certain guiding principles that can help orthopaedic surgeons implant biomechanically sound hip prostheses, lower the risk of taper damage, and prolong the survivorship of implants in THA. MACC is a complex degradation mechanism of the modular head-neck junction that involves both mechanical and chemical processes involving motion and fluid ingress. Impaction and assembly of the femoral head onto the trunnion can affect this rate of degradation. The literature has shown that pull-off force increases linearly with impaction force greater than 2 kN.[39] Thus, when assembling the head onto the neck, a concentric and coaxial force of at least 6 kN is recommended. Furthermore, it is important to ensure that the taper surface is clean at the time of assembly because blood and fat can not only decrease the pull-off force but also increase the rate of corrosion.[40]

Implant choice can also affect longevity of a THA. Taper angle, length, geometry, and diameter are all parameters that affect force distributions at a modular head-neck junction. Although there is notable evidence to suggest that a larger femoral head decreases dislocation risk, this increased head size coupled with decrease in trunnion size can lead to an increased risk of fretting wear and subsequent taper damage in certain femoral head-trunnion couples involving CoCr heads. The long-term effects of increased head-neck ratio are still being studied, and the pros and cons must be carefully weighed when choosing femoral heads > 36 mm in diameter in THA.[24]

Mixing and matching implants from different manufacturers also comes with its own risks. Each manufacturer has a different design and machining tolerances, and a 12/14 taper from one company is not always identical to a 12/14 taper from another company. Thus, when revising hips with a retained stem, it is important to pay attention to not only the taper size but also the taper tolerance limits, especially in the case of ceramic heads, where fit mismatch can lead to catastrophic head fractures.[38]

Patient selection and implant customization can also play a role in implant longevity. It is important to recognize that higher body mass index increases the risk of fatigue failure at the trunnion and constructs with neck extensions > 5 mm, extended offset stems, and other factors that increase the horizontal lever arm may increase the risk of MACC in this patient population. Thus, when tailoring the implants to patients, constructs that allow favorable biomechanical loading conditions at the modular head-neck junction must be chosen.[25]

Summary

With the introduction of the Morse taper to orthopaedic surgery, modularity at the head-neck junction provided the surgeon distinct advantages such as the ability to customize offset, version, and leg length to individual patient's anatomy in THA. However, modularity comes with its own drawbacks, and careful implant selection based on taper parameters and material properties is important to mitigate the risk of MACC and early implant failure.

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