REVIEW ARTICLE

Femoral taperosis
AN ACCIDENT WAITING TO HAPPEN?

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A modular femoral head–neck junction has practical advantages in total hip replacement. Taper fretting and corrosion have so far been an infrequent cause of revision. The role of design and manufacturing variables continues to be debated. Over the past decade several changes in technology and clinical practice might result in an increase in clinically significant taper fretting and corrosion. Those factors include an increased usage of large diameter (36 mm) heads, reduced femoral neck and taper dimensions, greater variability in taper assembly with smaller incision surgery, and higher taper stresses due to increased patient weight and/or physical activity. Additional studies are needed to determine the role of taper assembly compared with design, manufacturing and other implant variables.

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A modular femoral head–neck junction has practical advantages, and has become the standard for contemporary femoral stems in total hip replacement (THR). This junction permits intra-operative adjustments of limb length and offset, head diameter and material even after the stem is placed. In some cases modularity can also facilitate revision, and decreases femoral stem inventory.1 Taper design and manufacturing have not been standardised, and there are more than 30 varieties of head–neck taper in use. There are several variables in femoral tapers: proximal diameter, distal diameter, taper length, included angle, manufacturing tolerances, surface finish, and surface treatment.

This type of junction introduces potential modes of failure including component mismatch,2 disassociation,3 fretting and corrosion.4-8 In the 1980s and early 1990s, deterioration of the head–neck junction in situ occasionally necessitated revision,1,9,10 and improvements in taper design and manufacturing have reduced its contribution to clinical failure. However, several recent reports have demonstrated instances of fretting and/or corrosion of this modular junction in clinical failures which occur more commonly in association with larger diameter (> 32 mm) metal-on-metal (MoM) bearings.11-15 Are these technically advanced methods leading to a higher incidence of taper fretting and corrosion, and as a result, revision surgery?

History
The machine taper is a simple and versatile connection comprised of a gradually tapered shank and a matching hollowed-out spindle. Under axial load, the friction across the surface area of the interface can resist a large amount of torque, so that splines or keys are not required. The tapers can differ in the following ways: the diameter at the small end of the truncated cone (the minor diameter), the diameter at the large end of the truncated cone (the major diameter), and the axial distance between the two ends of the truncated cone. Stephen A. Morse invented the Morse taper in the 1860s, which is roughly 5/8 inches per foot (a relatively narrow taper angle) with the shortest shank being about 2 inches (5 cm).16

The taper in a THR is commonly referred to as a ‘Morse taper’, but the dimensions are outside those covered by the Morse patent and are shorter with larger taper angles. Femoral component head-neck modularity was popularised in the early 1980s. Taper sizes range from 8/10 mm distally to 14/16 mm proximally. It is important to note that femoral stem tapers are not made to standard specifications, and femoral heads should not be interchanged between designs, even if the nominal dimensions of the taper are the same (e.g. 12/14 mm).

Wear and corrosion of orthopaedic implants
There are variable stresses on a head–neck taper junction depending on the loading and movement of a particular patient. As a result modular taper junctions can fret and/or corrode, producing particles, metal ions, and other corrosion products.10,17 Fretting is surface...
damage caused by the mechanical interaction and relative motion between the two sides of the taper, which both alters the surface(s), and produces wear particles. The international standard definition of corrosion is the “physicochemical interaction between a metal and its environment which results in changes in the properties of the metal and which may often lead to impairment of the function of the metal, the environment, or the technical system of which these form a part”.

The basic reaction that occurs during corrosion is the loss of electrons from the metal atom to form free metal ions in solution, which can migrate away from the metal surface, or lead to the formation of metal oxides, metal chlorides or organometallic compounds. These products may be soluble or may precipitate out as solids. The solid oxidation products may be subdivided into those that form adherent compact oxide films and those that form non-adherent oxide, chloride, phosphate, or other particles that can migrate away from the metal surface.

Most alloys used for orthopaedic implants rely on the formation of a passive metal oxide film that prevents transport of metal ions and electrons across the film, and in turn prevents further oxidation from taking place. Mechanical factors, such as fretting or applied stresses, can cause the oxide film to abrade or fracture and expose the underlying metal, making it more susceptible to corrosion.

In order to continue corrosion reactions, the electrons that are left behind in the metal undergo a reduction reaction. A typical example in orthopaedic implants is the reduction of oxygen and water to form hydroxide. Reduction reactions can take place either very close to the corresponding oxidation reaction or far from it: as in a crevice corrosion reaction, the crevice solution becomes relatively depleted in oxygen and while continued oxidation takes place in the crevice, the reduction reaction occurs away from it. In order for corrosion reactions to progress, there must be a corresponding reduction reaction. If the reduction reaction is eliminated, then corrosion may be suppressed.

The second factor that governs the corrosion process is kinetic barriers that prevent corrosion by physical limitation of the rate at which oxidation or reduction processes can take place. The process of passivation, or the formation of a metal-oxide passive film on a metal surface, is an example of a kinetic limitation to corrosion. In general, kinetic barriers to corrosion prevent the migration of metal ions from the metal to the solution, the migration of anions from the solution to the metal, and the migration of electrons across the metal-solution interface. Passive oxide films are the best known forms of kinetic barriers to corrosion.

Conditions in the head–taper crevice permit local acidification to occur, causing a drop in the pH and ultimately changing the electrochemical environment surrounding the taper. The local drop in pH along with fretting can lead to the loss of passivity of the metal alloys. Although galvanic corrosion is thought normally to occur between dissimilar metals, it may occur following the loss of passivity from one surface of an intimate junction between similar metals.

There are multiple modes of corrosion when dealing with orthopaedic implants. It is important to recognise both electrochemical and mechanical forces can drive the corrosive process. Fretting, crevice, and galvanic corrosion may all play a role in the corrosive process at the modular taper junction.

Early taper issues
Titanium alloy stems (Ti6Al4V, ASTM F-136-79) were popularised in the 1980s as they provided decreased stiffness and greater biocompatibility when compared with their cobalt-chromium counterparts. However, titanium alloy has lower surface hardness, with less favourable wear characteristics as a bearing surface. Retrieval analyses of titanium heads revealed more scratching, burnishing and loss of sphericity compared with cobalt alloy heads (HS21, ASTM F-75).

The emergence of modular prosthesis permitted the mating of dissimilar metals at the time of surgery, and made it possible to combine the most appealing attributes of each alloy. When two different metals are placed in close contact in an electrolyte solution, there is a potential for galvanic corrosion to occur. The concern for galvanic corrosion increases when the combination of dissimilar metal alloys are coupled at the head-neck junction.

In a multicentre retrieval analysis of 231 modular hip implants, Goldberg et al used a semi-quantitative grading score to assess neck and head corrosion. The scores were significantly higher for mixed alloy versus similar alloy couples. Moderate to severe corrosion was observed in 28% of the heads of similar alloy couples and 42% of the heads of mixed alloy couples. Differences in corrosion scores were observed between components made from the same base alloy, but of differing metallurgical conditions. Corrosion and fretting scores tended to be higher for heads than necks.

Neck length did not have any effect on head and neck fretting or corrosion scores. Implantation time and flexural stiffness of the neck were predictors of head and neck corrosion and head fretting. The head and neck moment arm had a statistically significant effect on head and neck corrosion and head fretting scores. When considered together with implantation time and flexural stiffness, it no longer had a significant effect. Therefore predictive ability can be explained by implantation time and flexural rigidity; the head and neck moment arm had no effect on neck fretting.

The results of this study suggest that in vivo corrosion of modular hip taper interfaces is attributable to a mechanically assisted crevice corrosion process. Similar observations and conclusions had been made by Collier et al with galvanically-accelerated crevice corrosion seen in retrievals where the stem was titanium alloy and the head was cobalt-chrome. Cook, Barrack and Clemow observed wear and corrosion more commonly in mixed-alloy retrievals compared with single-alloy retrievals. In their study, stems with wear and corrosion were less likely to show histological bone ingrowth. However, none of these studies of taper corrosion reported the occurrence of significant soft-tissue reactions.
Biological considerations

Adverse local tissue reactions (ALTR)\textsuperscript{22} can occur secondary to corrosion at the modular femoral head–neck taper, regardless of the bearing, and their presentation is similar to the adverse local tissue reactions seen in patients with a metal-on-metal resurfacing (no taper). Elevated serum metal levels, particularly a differential elevation of serum cobalt with respect to chromium levels, can be helpful in establishing this diagnosis.

In 1988, Svensson et al\textsuperscript{23} reported the formation of a fulminant soft-tissue pseudotumour associated with a cementless cast cobalt–chromium total hip stem, (Lord prosthesis; Benoist Girard; Bagneux, France) and a modular cobalt-chromium head (polyethylene acetabular bearing). At 2.5 years post-surgery, a female patient complained of increasing pain in the buttock with distal radiation and had a slight limp. Angiography revealed a large, avascular soft-tissue mass, and there was grossly necrotic bone and soft tissue during surgery. Histology showed extensive necrosis, fibrosis, and inflammation dominated by lymphocytes, monocytes-macrophages, and eosinophils. Several small blood vessels exhibited obliterator necrotising arteritis. These histological findings are similar to what was later termed by Willert et al\textsuperscript{24} as aseptic lymphocyte-dominated vasculitis-associated lesion (ALVAL). The most salient finding on implant retrieval analysis was extensive corrosion of the modular.

Retrieval analyses reported by Urban et al\textsuperscript{25} in 1994 and Jacobs et al\textsuperscript{17} in 1995 showed that particles of metal oxides, metal chlorides, and chromium phosphate corrosion products were present on implants of ten designs from six manufacturers. The most abundant solid corrosion product on the implant and within the peri-prosthetic tissues was an amorphous chromium orthophosphate hydrate-rich material. Serum cobalt concentrations were elevated significantly in patients with implants that had moderate to severe corrosion in comparison with those with mild or no corrosion. Solid corrosion products from modular femoral stems may accelerate articular wear via a third body mechanism. Particles of these corrosion products capable of being phagocytosed may stimulate macrophage-mediated peri-prosthetic bone loss. Systemic dissemination of metallic corrosion products raises the issue of systemic toxicity, however, no overt evidence of metal toxicity was observed in this study.

In 2012, Cooper et al\textsuperscript{13} reported on ten patients with a metal-on-polyethylene THR, from three different manufacturers, who underwent revision surgery for corrosion at the modular head–neck junction between January 2009, and August 2011. These procedures represented 1.8% of the 569 revision THR they performed during that time. Patients (eight women and two men) initially presented with symptoms at a mean of 3.2 years (0.7 to 8.7) after their index procedure. Of The THR seven had a cobalt–chromium stem and head (three had a titanium alloy stem and cobalt–chromium head). In the group, eight hips had a head diameter ≤ 32 mm (two were 36 mm). All patients presented with pain or swelling around the hip, and two patients presented with recurrent instability. Serum cobalt levels were elevated prior to the revision THR and were typically more elevated than serum chromium levels were.

Surgical findings included large soft-tissue masses and surrounding tissue damage with visible corrosion at the femoral head-neck junction. The two patients who presented with instability had severe damage to the hip abductor musculature. Pathology specimens consistently demonstrated dense perivascular infiltration of lymphocytes and large areas of tissue necrosis, similar to an ALTR associated with metal-on-metal bearings. It is unclear what the specific stimulus is for such aggressive soft-tissue reactions, but they appear to be exclusively associated with cobalt-based alloys.

Current considerations

In a desire to increase impingement-free range of improvement and reduce dislocations,\textsuperscript{26} the use of larger diameter heads (> 32 mm) has increased substantially over the last decade, with many associated with metal-on-metal bearings. Although metal-on-metal bearings are rarely used in THR today, some lessons may generally apply. Concurrently, there has been a movement towards reducing femoral neck dimensions with smaller tapers, which can also increase the impingement-free range of improvement. Reduction in neck and taper dimensions also reduces flexural stiffness, which has been associated with increased fretting and corrosion.\textsuperscript{20}

Using a coordinate measuring machine, Langton et al\textsuperscript{12} measured the location, volumetric and linear wear rates of the (female) taper junctions on retrievals with metal-metal bearing diameters ≥ 36 mm. The rates of wear, and distribution of material loss from the taper surfaces, appeared to show that the primary factor leading to taper damage is an increased horizontal lever arm from the larger diameter heads acting on this junction. Taper wear rates appeared to be unaffected by bearing surface wear rates. There was a trend towards increasing taper wear and increasing head offset. Increased torsion did not appear to be a factor in taper wear. The role of manufacturing variables, such as taper tolerances and surface ridges, continues to be debated.

Head–neck taper assembly at the time of implantation is not standardised. The ‘cleanliness’ and impaction force of the taper both influence the resultant initial strength and integrity of the assembly,\textsuperscript{27,28} however, the relationship between the initial strength of the taper assembly and subsequent fretting and corrosion has not been established. Over the past decade there has been a trend toward smaller-incision surgery. It should be recognised that a smaller incision could compromise modular head–neck assembly, especially with larger diameter heads. Other considerations include the increase in average patient weight, and more instances of THR in younger and more active people, with an inevitable aggregate increase in the stresses on the taper. As a result, there could be an increase in clinically
significant taper fretting and corrosion of hips implanted during the last ten years.

Recent retrieval analyses indicate significantly reduced taper fretting and corrosion with ceramic heads. Nevertheless, there are relatively few retrieval analyses of larger diameter (≥36 mm) ceramic heads. Regardless of diameter, using a ceramic head on a titanium alloy stem eliminates cobalt–chromium from the THR and essentially eliminates the risk of ALTR in exchange for a small risk of ceramic head fracture.

In summary, clinically significant taper corrosion is uncommon. In the majority of cases, the femoral head–neck junction is not an issue. The role of design and manufacturing variables continues to be debated. Over the past decade several changes in technology and clinical practice might result in an increase in clinically significant taper fretting and corrosion. Those factors include an increased use of large diameter (≥36 mm) heads, reduced femoral neck and taper dimensions, greater variability in taper assembly with smaller incision surgery, and higher taper stresses due to increasing patient weight and/or physical activity. There have been multiple studies recently evaluating possible diagnostic criteria as well as the intra-operative findings associated with a painful THR secondary to mechanically assisted crevice corrosion of the taper junction. The gross and histological findings of the peri-articular tissue aid in the understanding of the pathological process and can help dictate the optimal surgical treatment. Additional studies are needed to elucidate the role of taper assembly compared with design, manufacturing, and other implant variables. Additional studies are also needed to define the pathophysiology of aggressive soft-tissue reactions associated with cobalt-based alloys.

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References