Modularity of the Femoral Component in Total Hip Arthroplasty

Abstract

Modular femoral components have been developed to aid in recreating native femoral version, limb length, and offset in total hip arthroplasty. Use of modular implants results in cost savings, as well. Inventory can be reduced while allowing intraoperative flexibility and options. With modular implants, the femoral prosthesis can be built in situ, which is helpful in minimizing incision length and surgical dissection. However, additional modular junctions are associated with increased concern for component failure through taper fretting, fatigue fracture, and local corrosion, which may contribute to elevated serum metal ion levels. The recent trend toward using larger diameter femoral heads may impart higher loads and stress than were seen previously. Although modular components offer a plethora of intraoperative options in primary and revision total hip arthroplasty, the long-term effects of these additional junctions remains unknown.

Total hip arthroplasty (THA) is one of the most successful surgical procedures, offering significant improvement in patient quality of life and function. In the 1960s, early monoblock implants were designed for THA. These included the cemented Charnley stem (DePuy International Ltd, Leeds, UK) and Exeter hip (Howmedica International Ltd, London, UK); both have shown good long-term survivorship and clinical outcomes.

However, significant limitations remained in fine-tuning leg length and offset because these parameters could not be addressed by modifying the implant itself. Instead, surgeons relied on rigorous preoperative planning, meticulous intraoperative cementing technique, and adjustment in abductor tension via the transtrochanteric approach to enhance stability and outcomes. Although monoblock stems have demonstrated excellent long-term results, most surgeons today use implants with at least one modular junction.

Findings that leg length, offset, and version can differ greatly between patients have spurred the development of modular implants. Attempts to address differences in patient anatomy and to restore the femoral head center led to the development of modular femoral implants for use in both primary and revision THA. However, processes such as corrosion, fretting, and fatigue failure of implants have been increasingly recognized as surgeon experience with dual modular implants continues to increase.

Additionally, large-diameter (eg, 32- and 36-mm) and jumbo (eg, 40- and 44-mm) femoral heads are being...
used in primary and revision surgery to prevent impingement and minimize the risk of dislocation.18

The role of frictional torque on modular junctions in the setting of large-diameter femoral heads in THA remains poorly defined. Increasing femoral head size correlates with increased frictional torque at the bearing surface, but the direct impact of this finding on modular junctions is not well defined, and increased torque has not been associated with failure.9 Recent evidence suggests a revision rate of approximately 8% to 15% in large-head metal-on-metal THA at midterm follow-up.10,11 Although fretting and galvanic and crevice corrosion have been well described, the effects of local and systemic exposure to increased metal ions from corrosion byproducts remains unknown.

The use of modular implants in the current active and more demanding patient population undergoing THA warrants close clinical and radiographic monitoring. Surveillance of serum ion levels may be warranted, as well.

**Head-neck Modularity**

The introduction of the modular femoral head-neck junction was the first step in the evolution of modularity. A modular head-neck junction allows the use of metallic alloys or ceramic head alternatives, adjustment of leg length and offset, and replacement of the bearing in the presence of wear. Fine-tuning leg length and hip offset can correct limb-length discrepancies and augment abductor function, thereby enhancing patient outcome. Removal of the modular head may be useful in achieving adequate exposure during hip revision procedures, including acetabular revision. The modular head can be exchanged to increase either neck length or the diameter of the femoral head in the setting of an unstable THA; acceptable reductions in dislocation rates have been noted.12-14 Optimizing the head-neck ratio with the use of modular implants can thus reduce the risk of dislocation and increase impingement-free range of motion following THA.15,16

Modularity of the head-neck junction usually occurs at a Morse taper, which functions as a means of joining two rotating components in a THA construct. The trunnion or male portion of the taper compresses the bore or female portion as it expands, leading to interlocking of the two components, thereby providing both axial and rotational stability.17 Under normal loading, the cold weld between the two components is strong, and joint strength increases with in vivo loading.18 Minimizing tolerances and dimensional mismatch between the components reduces relative motion and resultant corrosion.

Component tapers are made in multiple sizes and angles based on the implant design and manufacturer specifications, and the surgeon must take care to avoid component mismatch. Use of femoral heads and stems by different manufacturers should be avoided. Although the shape of the neck (ie, trapezoidal versus circular) plays a role in implant impingement, Barrack et al19 noted that the presence of a larger head-neck taper (eg, 14/16) may contribute to an increased dislocation rate because prosthetic impingement occurs sooner in the arc of motion. Range of motion was found to be 76% lower with a larger diameter, long taper, and circular neck than with a smaller diameter, shorter taper with a trapezoidal femoral neck. However, large-diameter tapers offer increased strength and resistance to fatigue fracture. The recent trend in the use of smaller tapers (eg, 12/14) and maximizing the head-neck ratio holds the potential for increased fretting and corrosion at these junctions (Figure 1).

Dissociation of the head from the neck is a rare complication with modular implants. It has been reported mostly in the setting of trauma, with mismatched head-neck tapers, and during closed reduction of dislocated THA.20 The incidence of dissociation with modern taper designs remains unknown; there is a paucity of peer-reviewed literature on the topic. Biomechanical studies suggest that the presence of debris such as blood and fat places the head-neck taper at risk of dissociation at forces lower than those required to disrupt a pristine junction.21 However, adequate cleaning of the trunnion returns the modular implants to a state in which greater force is necessary to cause dissociation. Damage of the taper, either through corrosion or from revision surgery, precludes placement of a new modular head. Quantification of Morse taper damage has not been studied in significant detail. Currently, there are no guidelines regarding the extent of damage or corrosion at the Morse taper sufficient to warrant revision of the entire femoral component.

**Dual Modular or Proximal Modular Femoral Stems**

Femoral stems with two junctions allow even greater capacity for independent matching of proximal femoral version, offset, and limb length with metaphyseal/stem body size (Figure 2). Several studies have reported success with femoral components with multiple taper junctions in both the primary and revision settings.22-24 Such dual modular stems allow assembly of the prosthesis in...
situ, with insertion of the stem body or metaphyseal sleeve performed independently of insertion of the modular femoral neck or stem, respectively. This limits the amount of surgical dissection needed for safe component implantation. It is important to differentiate the varying design features of femoral components with metaphyseal neck-stem modularity (eg, S-ROM [DePuy, Warsaw, IN], Emperion [Smith & Nephew, Memphis, TN]) from those with modular neck or proximal modular stems (eg, Profemur Z [Wright Medical Technology, Arlington, TN], Kinectiv [Zimmer, Warsaw, IN], Rejuvenate [Stryker, Mahwah, NJ]).

A metaphyseal modular stem differs from a proximal modular stem in that the distal junction of the implant...
plant is located at the metaphyseal-diaphyseal junction of the femur and usually lies distal to the femoral neck osteotomy. In contrast, the distal junction in a proximal modular stem is usually proximal to the femoral neck osteotomy and is unsupported by host bone. These taper connections are subject to different physiologic stresses based on the location of the modular junction.

The metaphyseal modular design (eg, S-ROM) has been available for use in primary THA for more than 15 years, with excellent reported long-term clinical results. In 795 primary THAs in which S-ROM was used, Cameron et al\textsuperscript{22} reported low rates of aseptic loosening and no cases of hardware fatigue failure at a mean follow-up of 11 years. Similarly, Christie et al\textsuperscript{25} reported a low revision rate in primary THA, with 99.4% survivorship and no stem failures at a mean follow-up of 5.3 years. Reported follow-up times with modular neck stem designs are short because of their more recent introduction, but preliminary results have suggested similar rates of survivorship.\textsuperscript{26}

Although an additional junction offers many advantages, there is the potential for neck-body dissociation (Figure 3) and increasing amounts of metal debris cumulatively generated at both tapers. This effect may be potentiated with the addition of a metal-on-metal articulation; in these cases, circulating serum ion levels are usually elevated as a result of wear at the bearing surface.\textsuperscript{27} In a retrieval study of 16 dual modular implants of a single design, Kop and Swarts\textsuperscript{28} showed notable fretting as well as crevice and intergranular corrosion at the neck-stem interface in six cases. More importantly, corrosion was higher at the neck-stem interface, likely secondary to increased mechanical stresses, than it was at the head-neck interface. Similarly, in the S-ROM, stem fretting has been shown at the metaphyseal neck-stem interface, although debris generated was similar in magnitude to that created by the head-neck interface and was much smaller than the amount of debris generated at the THA bearing surface.\textsuperscript{24,30} Despite concerns, long-term outcomes with this device do not appear to be compromised.

In the retrieval laboratory at our institution, we examined 14 titanium alloy (Ti-6Al-4V) or cobalt-chromium (CoCr) modular neck junctions of three proximal modular neck designs that were removed at a mean of 3 months for acute infection, instability, periprosthetic femoral fracture, or fracture of the modular neck.\textsuperscript{31} Using light and electron microscopy, we noted significant fretting corrosion at the distal neck/body junction in seven stems, with two associated fatigue fractures (Figure 4). Our results suggest that fretting and crevice corrosion are real concerns clinically with such modular components.

In comparison, Kretzer et al\textsuperscript{32} examined metal release and corrosion effects of five different titanium implants of variable modularity. No
correlation was found between increased modularity and fretting corrosion or titanium ion release under simulated in vivo conditions. Although electron microscopy revealed fretting in all junctions tested, the authors concluded that corrosion was not excessive in any implant tested.

Although modularity provides the surgeon with more options intraoperatively than do monoblock implants, one must question the use of additional modularity in a primary THA in which native anatomy is not grossly distorted and can be recreated with traditional components. In a retrospective study, Regis et al noted no difference in dislocation rates between a proximal modular stem and a standard THA stem. Similarly, Lombardi et al noted no clinical differences in a retrospective review of two consecutive series of patients undergoing primary cementless THA in which one group was fitted with nonmodular stems and the other was fitted with a metaphysial modular stem. Currently, clinical outcomes are similar for monoblock, single modular, and dual modular femoral components, with advantages and disadvantages with each option.

In some specific situations in the setting of primary THA, modularity is helpful in optimizing appropriate fixation and soft-tissue balancing. In persons with hip dysplasia, modular components facilitate diaphyseal fixation independent of distorted proximal femoral anatomy. Abnormal femoral neck version relative to the epicondylar axis of the femur can be overcome by making adjustments at a modular junction without compromising hip stability, creating limb-length inequality, or altering the tension of the abductor musculature. Most dual modular stems have more options in length, offset, and version than do standard THA components, which allows surgeons greater capability to fine-tune stability and head center location. In revision THA, in which bone quality and fixation are often less predictable, implant height and offset can be adjusted independent of distal fixation and may require fine adjustments once distal purchase is achieved.

In our experience at a high-volume academic center, modular femoral stem components cost 15% to 25% more than do standard femoral stem components for primary or revision THA.

**Fatigue Fracture in Dual or Proximal Modular Stems**

Fracture of the femoral stem is a rare complication that is estimated to account for <1% of THA revisions. Several case reports have been published on fatigue fractures of proximal modular stems (Figure 5). Skendzel et al noted on two cases of fatigue fracture with proximal modular stems. They described an association between implant design (ie, long varus modular neck) and patient factors such as obesity with eventual implant failure. The authors noted a 32.7% decrease in bending moment when a short varus neck was used compared with a longer neck component. Intuitively, a longer lever arm and greater weight (ie, head size) at one end of a junction leads to a greater bending moment at that junction.

To date, most fatigue fractures of proximal modular stems have occurred in implants with a titanium alloy coupling. In four of the six reported cases, extended trochanteric osteotomy was required during revision surgery because the primary femoral stem could not be salvaged, secondary either to damage to the implant or to the presence of retained neck fragments. Thus, failure of proximal modular implants is associated with substantial morbidity and carries the risk of potential complications because simple modular component exchange does not seem to be a valid surgical option in many of these cases.

The use of CoCr alloy instead of titanium in neck adapters may reduce the risk of fracture at the junctions of proximal modular femoral stems. In a retrieval analysis of 68 failures of a titanium neck adapter in a single implant design, Grupp et al noted significant micromotion, which led to fretting and crevice corrosion. Bone and particle contamination within the interface accelerated fa-
Fatigue properties within the titanium adapter. In a laboratory setting, the same group showed diminished micromotion with the use of a CoCr adapter; no clinical outcomes were reported.40 The occurrence of premature fatigue fractures with titanium adapters led to the adoption of a CoCr alloy adapter in some stem designs. Enthusiasm for this enhanced strength must be weighed against the introduction of an additional potential source of metal ion generation. Only long-term data will justify widespread adoption of this material.

Although rare, fracture of the femoral component can occur in modular revision components that have a metaphyseal-diaphyseal junction. In a retrospective review of a titanium alloy modular revision stem, Lakanstein et al41 noted six stem fractures at the mid stem junction. The authors concluded that a fretting fatigue mechanism, followed by a bending moment, led to implant failure (Figure 6). Excessive body weight and lack of proximal osseous support were identified as risk factors for failure of the revision stems. Chu et al42 determined through biomechanical studies that forces across implant junctions can be reduced as much as 55% in the presence of stable bony support. In planning for revision cases with minimal proximal bony support, the surgeon must consider the taper junction and the forces that may be incurred by this connection.

Fracture at the modular junction of femoral stems is multifactorial and unpredictable. Patient factors such as obesity and lack of proximal femoral osseous support with revision components, coupled with the increasing use of larger diameter heads in THA, may play a role in these failures. The role of increased frictional torque on modular junctions from the use of large or jumbo femoral heads remains unclear. Further in vivo and in vitro assessment is needed to quantify the impact of head size on taper corrosion and fretting.

Corrosion remains the chief culprit in the failure of modular implants; understanding the processes involved in corrosion may lead to further improvement in the design of proximal modular femoral stems.

**Modularity and Corrosion**

Single and dual modular femoral stems are typically composed of titanium or CoCr, both of which can form a protective surface oxide layer (ie, self-passivation) that aids in resisting corrosion, thereby conferring a greater degree of corrosion resistance and biocompatibility.43 As stresses are placed on these metallic implants, the oxide film layers may be repeatedly disrupted, particularly in the setting of junctional fretting.44 This disruption leads to a vicious cycle of recurrent self-passivation and oxygen depletion, which ultimately results in a harsh local microenvironment.45 As the cycle repeats, the ability to form a stabilizing surface coating is reduced, and regardless of its composition, the exposed metal becomes susceptible to corrosion. Resultant metal ion release may occur, which contributes to elevated serum metal ion levels. Repeat fracture of the passivation films can hasten taper fretting and junctional crevice corrosion, resulting in loss of mechanical integrity of the implant as well as local tissue infiltration and adverse periprosthetic tissue reactions.46

Corrosion at the head-neck taper may be caused by multiple mechanisms (eg, crevice, fretting, galvanic). The presence of a small gap between the two components allows fluid to enter and create crevice corrosion at the Morse taper. Fretting corrosion can be caused by small-scale movement of the head relative to the neck, the neck to the body, or the proximal body to the distal stem. Galvanic corrosion occurs in any mixed-metal system in which fluid is present, but it is most likely to occur in titanium alloy stems mated to CoCr heads.47

The incidence of crevice corrosion at the head-neck interface has been reported to be 35% to 40% in tapers of mixed-metal systems and 9% to 28% in single alloy systems.48,49 Fretting corrosion appears to be higher in mixed-metal systems, particularly in devices with a titanium alloy stem coupled with a CoCr femoral head.50 The amount of corrosion seen at the junction is time-dependent and is accelerated by mechanical stresses placed on the taper. Increased corrosion at the taper correlates with in-
creased local and systemic exposure to metal particles, although the sequelae of increased ion exposure remain ill-defined and unknown.\textsuperscript{51,52} Even in the well-functioning THA implant, serum titanium levels can be approximately threefold higher and CoCr levels approximately fivefold higher than in control subjects; systemic exposure is believed to originate from the head-neck taper.\textsuperscript{52}

Fretting corrosion appears to be a major source of failure at modular junctions, with longer necks associated with increased corrosion.\textsuperscript{53} In the future, the use of ceramic heads or alternative materials may remain a valid option when the goal is to reduce fretting corrosion at the head-neck interface. In one study of a single implant design, fretting corrosion at the head-neck junction was found to be significantly lower with a zirconia head than with a cobalt alloy head when coupled with a cobalt stem ($P < 0.05$).\textsuperscript{54} Galvanic corrosion does not occur with ceramic heads because there is no mixed-metal system. However, ceramic heads have their own risks secondary to their brittle nature and low fracture toughness.

Corrosion products from the head-neck interface can cause an inflammatory response that results in local osteolysis and synovitis.\textsuperscript{56,49,53} Metallic particles from secondary nonbearing surfaces have been found in end-stage organs.\textsuperscript{55} This finding was more prevalent in patients with failed components than in persons with well-functioning components. It is possible that corrosion at the modular junction may potentiate the production of metal ions at the bearing surface in metal-on-metal THAs or adjacent taper junctions. Although inferior clinical outcomes secondary to corrosion at modular junctions cannot be definitively shown, this remains an area of concern. The surgeon must be aware of the underlying metallurgy and the implications of modularity in femoral implants because there may be patient factors (eg, anatomy, body mass index) and surgical factors that make additional modularity and potential exposure to corrosion products undesirable.

The byproducts of corrosion can be characteristic of the affected metals at taper junctions. Chromium phosphate (CrPO$_4$) is a unique corrosion product that is encountered with CoCr and stainless steel (SS) alloy components.\textsuperscript{56} CrPO$_4$ particles have been associated with corrosion at the femoral head-neck junction, and these particles have been isolated in the local periprosthetic tissues in both single- and mixed-metal implants. In vitro studies show that CrPO$_4$ is a potent inflammatory pathway activator—a biologic process that leads to bone resorption. Clinically, distal femoral osteolytic reactions surrounding cementless femoral components in THA have been seen in response to the presence of CrPO$_4$ particles.\textsuperscript{59}

Excess cobalt levels in synovial fluid and serum resulting from metallosis and corrosion have been linked with increased serum and urine levels of circulating ions and have been implicated in the occurrence of thyroiditis, auditory disturbance, and granulomatous lesions.\textsuperscript{57} Metallosis can occur when a junction is not functioning properly as well as in the presence of third-body wear at a junction. A recently published report noted two cases of arthroprosthetic coxalitis, in which increased cobalt ion levels were implicated in systemic symptoms in the presence of a malfunctioning bearing surface or taper connect.\textsuperscript{58} To our knowledge, there is no study to date that links the number of junctions in an implant and serum ion levels.

SS is widely used outside the United States in the interest of reducing costs. A high-nitrogen SS stem costs approximately 50% less than an equivalent stem made of CoCr. Fracture of modern SS stems is exceedingly rare. Of the >450,000 Exeter Universal stems (Howmedica) implanted, manufacturers reported only 16 fractures at late follow-up with initial designs and metallurgy.\textsuperscript{59} Fracture with the Charnley low-friction arthroplasty stem has been estimated to be approximately 0.23%.\textsuperscript{60} One study noted that, of the few stem fractures through the neck documented with a cemented tapered polished stem design (eg, Exeter Universal, stainless steel CPT 6 Degree stem [Zimmer], and C-Stem [DePuy]), patients were larger, active, and had well-cemented stems in broader canals.\textsuperscript{61} Debris generated at the modular junctions of SS femoral stems can be significant, as well. Gilbert et al\textsuperscript{62} investigated the effects of in vitro corrosion from various cycling loading forces on modular tapers made from SS/CoCr and CoCr/CoCr. The junctions of SS necks and CoCr heads were found to be more susceptible to fretting corrosion in all conditions tested (ie, variation in offset, media, and cyclic loading).

### Summary

Modular femoral components were developed to address the issues of challenging surgical technique in implantation of monoblock femoral components in THA, the inability to exchange modular components in the setting of wear or bearing damage, and the desire to closely match patient anatomy. Dual or proximal modular stems have increased the intraoperative options, essentially uncoupling femoral offset, limb length, and version from the femoral component body. Modular stems in revision THA are also available to ensure adequate distal fixation with multiple proximal body options to
manages varying levels of bone loss. In the setting of bone loss, adequate distal fixation is more difficult to restore with standard implants. Although modularity allows extensive intraoperative flexibility, several potential and confirmed disadvantages exist, including risk of fracture, fracture and corrosion and increased systemic exposure to metal ions and debris. Long-term follow-up is required to determine the impact of increasing modularity in primary THA.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, references 1, 2, and 52 are level II studies. References 8, 16, 19, 33, 34, and 41 are level III studies. References 3-7, 9, 10, 12-15, 18, 20-28, 30-32, 35-40, 42, 44-50, 53-55, and 57-62 are level IV studies. References 17, 29, 43, 51, and 56 are level V expert opinion.

References printed in bold type are those published within the past 5 years.

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