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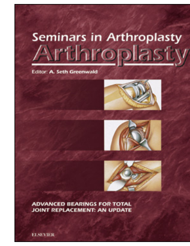

Femoral neck modularity: A bridge too far—Affirms

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ABSTRACT

The use of femoral stems with dual-taper modularity in total hip arthroplasty offers increased flexibility in restoring hip-center anatomy. Independent of femoral fixation, the modular neck offers the surgeon additional options in recreating femoral version, correcting limb length, and altering offset. Additionally, proponents cite smaller incisions, less dissection, reduced impingement and dislocation, and ease of revision. However, adverse events associated with modular femoral neck usage, including local and systemic effects of corrosion, fracture, and complexities of revision, are now well documented. This review highlights the most current basic science and clinical literature regarding the complications associated with modular femoral necks and their mechanisms of failure.

1. Introduction

As modern total hip arthroplasty (THA) evolved, femoral stems with dual-taper modularity were introduced in the 1980s to further refine how leg length, offset, and femoral version were re-created [1]. The modular head–neck junction allows the surgeon additional options to adjust the aforementioned variables independently of femoral stem fixation, more accurately restoring the hip-center and native anatomy. Proponents advocate that the increased intraoperative flexibility results in more appropriate soft tissue tension and joint biomechanics, ultimately decreasing incidence of mechanical impingement and dislocation events. Authors believed that the ability to build and theoretically disassemble the prosthesis “in situ” would lead to smaller incisions, less dissection, and simpler revisions in cases of a well-fixed stem [2–5].

As clinical failures began to surface in the operating room and appear in the published literature, concerns regarding the additional modular interface were raised. The various mechanisms of failure included fractures, dissociation at the modular neck–stem junction, and multiple forms of corrosion leading to local and systemic sequelae [6–32]. The sequelae of corrosion and metallosis have been observed in both the adjacent and distant soft tissues; however, their ultimate long-term clinical significance to date is not fully understood [21–32]. According to Australian registry data, the overall revision rate of dual modular femoral stems is twice that of fixed femoral necks (8.9% versus 4.2%), and during revision operations, failure to disassemble the neck from the stem has been observed [33,34]. As the clinical data mount, it is clear that the potential benefits of neck–stem modularity may come at a significant cost. Gaining a more complete understanding of the modular junction failure mechanisms

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currently is an important research initiative, and the authors' results to date are summarized below.

2. Corrosion in modular junctions

Corrosion between two opposing metal surfaces is inevitable given enough time [10,19,31,32,35–38]. As such, THA corrosion most likely will occur at any and all metal–metal junctions (including modular necks) [3,6–8,10,11,39–41]. With regard to the corrosion cascade, both cobalt–chromium (CoCr) and titanium (Ti) implants form a biocompatible passivation layer of inert metal oxide that, when intact, confers corrosion resistance; however, corrosion can begin if the layer is disrupted [10,11,42–44]. Corrosion at these junctions occurs through several mechanisms. First, pitting corrosion occurs from small defects in the passivation layer. Next, crevice corrosion can begin once microscopic cracks form in the passivation layer that is sequestered from the local environment. Lastly, galvanic corrosion occurs once two dissimilar metals create an electrical potential as a result of the microenvironment [10–12].

The corrosion cascade likely starts with fretting (movement on the order of $<100\ \mu m$) at the metal–metal junction, which disrupts the passivation layer [36]. When disrupted, this layer repassivates as the surrounding aqueous solution delivers oxygen to re-form the protective layer. Continued motion causes this passivation layer to be repeatedly fractured and reformed [10,45]. As fissures form and deepen at these sites, aqueous solutions cannot penetrate effectively to donate oxygen radicals, resulting in crevice corrosion and localized pitting corrosion [12]. Over time, due to oxygen sequestration from repassivation, the local environment is changed, causing a buildup of hydrogen and chloride ions. This effectively lowers the pH and can aid in the formation of galvanic cells [12,45]. This microenvironment can accelerate the corrosion process, leading to further damage of the implant [11,46–49].

Corrosion at metal–metal junctions is accelerated when under mechanical load, which is termed mechanically assisted corrosion (MAC) [10,11,42,45]. MAC accelerates fracture of the passivation layer leading to unprotected metal and active dissolution and repassivation reactions [11,45]. A byproduct of these reactions is hydrogen, and cobalt–chromium and Ti alloys have great affinity for hydrogen [45]. Free hydrogen interacts with the lattice of the microstructure of the bare metal in a process known as hydrogen embrittlement [45]. This process is characterized by degradation of the mechanical properties of the metal causing a decrease in ductility as well as tensile and fatigue strength [45,50,51]. Crack formation and propagation is intimately tied to embrittlement [45]. As the hydrogen concentration increases, the hydrogen-containing phase of the metal also increases. This ultimately may lead to hydrogen-induced cracking, a complex reaction that causes cracking and delamination of the most superficial layers of the implant [45]. Rodrigues et al. [45] looked at the elemental analysis of Ti tapers after retrieval and found that the taper samples showed a significantly higher hydrogen concentration than control samples, which the authors attributed to corrosion-induced hydrogen embrittlement.

Weber et al. [33] also reported hydrogen pneumarthrosis as a cause of pain and implant failure in a recent case report of six patients who had undergone primary THA with a modular neck. An emerging thought is that this process may not require continued fretting corrosion to propagate the pitting and cracking [10]. The reaction may perpetuate due to the local microenvironment created by internal oxide formation. This oxide-induced stress corrosion cracking (OISCC) can occur even when externally applied tensile stresses are nominal [10,42]. As stated by Gilbert et al. [10], the oxide within these pits and cracks appears to reorganize, developing new channels for fluid transport and additional reactions allowing OISCC to occur.

3. Head–neck junction

The effects of corrosion have been examined at both the femoral head–neck junction and the femoral neck–stem junction [3,6–8,11,39–41,52]. Several retrieval studies have shown that more corrosion occurs at the neck–stem junction than at the head–neck junction, likely due to the higher mechanical loads [11,37–39,43]. However, no metal–metal junction is spared from corrosion [10,32,37–39,43]. In a study of 78 retrieved modular hip implants of a single design, Huot Carlson et al. [53] found that, of the head–neck junctions of dissimilar alloys, 54% showed corrosion and 88% fretting, compared with 88% corrosion and 65% fretting in the group of neck–stem junctions of similar alloys. Gill et al. [30] corroborated these results using a finite element analysis in a cohort of modular neck THA components and reported that the neck–stem junction is eccentrically loaded, leading to higher stresses when compared with the neck–head junction, and thus higher corrosion rates are expected (Fig. 1).

Corrosion can occur at any metal–metal interface whether Ti–Ti, CoCr–Ti, or CoCr–CoCr, as well as the metal portion of a metal–ceramic interface [11,19,31,32,36,37,54,55]. No clear consensus exists as to which metal–metal or metal–ceramic combination is optimal. Some have advocated for CoCr rather than Ti necks due to lower micromotion and increased fatigue strength[39,43]; however, others have found the opposite [37,40] Goldberg et al. [40] reported significantly higher magnitudes of fretting and corrosion at the head–neck junction with mixed metal couples. Kop et al. [19] examined 57 modular necks from seven THA modular designs and found that 62% of CoCr components showed corrosion and 90% displayed fretting as compared with 30% of the Ti components showing corrosion and 50% displayed fretting.

At the head–neck junction, femoral head size and type (ceramic versus metal) affect corrosion [32,36]. Larger diameter femoral heads produce increased torque [7,32,56], which leads to increased stresses at the metal–metal interfaces and causes progression of local corrosion [32]. Recent studies have shown that using a ceramic femoral head reduces the overall amount of corrosion, specifically at the head–neck junction; however, the basic mechanism of corrosion remains the same for the remaining metal of the male portion of the junction [36,55].

Other factors affecting corrosion include the geometries of the neck and head. Geometry of the modular neck