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CLINICAL RESEARCH

Modern Trunnions Are More Flexible: A Mechanical Analysis of THA Taper Designs

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Abstract
Background There is renewed concern surrounding the potential for corrosion at the modular head-neck junction to cause early failure in contemporary THAs. Although taper corrosion involves a complex interplay of many factors, a previous study suggested that a decrease in flexural rigidity of the femoral trunnion may be associated with an increased likelihood of corrosion at retrieval.
Questions/purposes By analyzing a large revision retrieval database of femoral stems released during a span of three decades, we asked: (1) how much does flexural rigidity vary among different taper designs; (2) what is the contribution of taper geometry alone to flexural rigidity of the femoral trunnion; and (3) how have flexural rigidity and taper length changed with time in this group of revised retrievals?
Methods A dual-center retrieval analysis of 85 modular femoral stems released between 1983 and 2012 was performed, and the flexural rigidity and length of the femoral trunnions were determined. These stems were implanted between 1991 and 2012 and retrieved at revision or removal surgery between 2004 and 2012. There were 10 different taper designs made from five different metal alloys from 16 manufacturers. Digital calipers were used to measure taper geometries by two independent observers.
Results Median flexural rigidity was 228 N-m^2; however, there was a wide range of values among the various stems spanning nearly an order of magnitude between the most

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flexible (80 N-m^2) and most rigid (623 N-m^2) trunnions, which was partly attributable to the taper geometry and to the material properties of the base alloy. There was a negative correlation between flexural rigidity and length of the trunnion and release date of the stem.

Conclusions There is wide variability in flexural rigidity of various taper designs, with a trend toward trunnions becoming shorter and less rigid with time.

Clinical Relevance This temporal trend may partly explain why taper corrosion is being seen with increasing frequency in modern THAs.

Introduction

Modularity at the head-neck junction of the femoral component in THA confers several advantages, including the ability to intraoperatively adjust head size, neck length, and choice of bearing surface after femoral fixation has been achieved. Should revision arthroplasty be required, it also allows for easier surgical exposure and more potential options [8, 14]. Shortly after the introduction of modularity in THA, issues of fretting and corrosion at the modular head-neck junction were identified [30], and have since been well documented [10, 12, 13, 18, 28]. Early retrieval analyses of femoral components attempted to identify the cause of corrosion, and although initially thought to be galvanic [7], an increasing body of literature points toward a mechanical etiology secondary to fretting and crevice-associated mechanisms of corrosion at the head-neck junction [4, 22]. Concerns regarding the potential local and systemic effects of soluble and particulate debris from corrosion at the head-neck interface were expressed as these modular implants became available [23–25, 37]. Because of early reports of corrosion, fretting, and implant fracture at the modular interface [8, 19] with associated biologic reactions [35], improvements in manufacturing and design subsequently were made, including making the femoral trunnions larger and more rigid. These changes curtailed initial concerns and helped lead to universal acceptance of these versatile implants.

Recently, there has been renewed concern surrounding the potential for corrosion at the modular head-neck junction to cause early failure of modern hip implants. Increasing attention to local and systemic effects of wear debris and metallosis in patients with metal-on-metal devices led to the discovery that corrosion at the head-neck taper can be the cause for adverse local tissue reactions, even in patients without a metal-on-metal bearing surface [6, 11, 14, 29, 31, 32, 39]. Although taper corrosion involves a complex interplay of many factors, a previous study [23] correlated higher flexural rigidity of the femoral trunnion with a decreased likelihood of corrosion.

There has been an ongoing evolution in trunnion design during the last several decades with implant manufacturers offering smaller trunnion designs with the rationale that an increased head-neck ratio may help prevent component impingement and reduce the risk of postoperative instability [1]. Despite these design and manufacturing changes, including the introduction of numerous novel taper geometries, to our knowledge there has been no published documentation regarding how trunnions have changed with time and how these changes may have influenced biomechanical properties of the femoral trunnion.

By analyzing a large revision retrieval database of femoral stems released during a span of three decades, we asked: (1) how much does flexural rigidity vary among different taper designs; (2) what is the contribution of taper geometry alone to flexural rigidity of the femoral trunnion; and (3) how have flexural rigidity and taper length changed with time in this group of revised retrievals?

Table 1. Manufacturers of the 85 stems included in the retrieval analysis

Modern company	Historical company	Number
Biomet (Warsaw, IN, USA)	Biomet	6
DePuy (Warsaw, IN, USA)	Codman (Raynham, MA, USA)	1
	DePuy	15
	Johnson & Johnson (J&J)	1
	Joint Medical Products (JMP; Stamford, CT, USA)	1
	Landos Biomecanique (Chaumont, France)	1
Smith & Nephew (S&N; Memphis, TN, USA)	Richards (Memphis, TN, USA)	2
	Smith & Nephew	8
Stryker (Mahwah, NJ, USA)	Osteonics (Allendale, NJ, USA)	5
	Howmedica (Rutherford, NJ, USA)	7
	Stryker	4
Wright Medical Technology (WMT; Arlington, TN, USA)	LINK (Hamburg, Germany)	2
	Orthomet (Minneapolis, MN, USA)	4
	Wright Medical Technology	3
Zimmer (Warsaw, IN, USA)	Protek (Bern, Switzerland)	2
	Zimmer	23

Materials and Methods

An analysis of 85 unique femoral stem designs retrieved from two separate centers at the time of revision surgery was performed; none was retrieved for a diagnosis related

Table 2. Taper geometries included in the retrieval analysis

Taper*	Number
C-Taper	5
V40™ (5° 40′)	9
Type I	5
Type II	1
PCA® (2° 52′)	2
6°	4
10/12	1
11/13	2
12/14	51
14/16	5

* Tapers can be described by either the taper angle (in degrees) or proximal and distal diameters (in mm). Some designs are proprietary to specific manufacturers and are given trade names. There is no universal standard for tapers, with considerable variability between or in some manufacturers for different stems.

to a problem at the head-neck taper junction. Stems originally were implanted during a 22-year period from 1991 to 2012. The 85 stems represented designs from 16 different historical implant manufacturers, several of which have since merged (Table 1). These represent approximately 25% of all stem designs with modular head-neck junctions indexed in a comprehensive implant atlas [2]. The stem designs had 10 different taper geometries (Table 2), some of which are no longer in use. Data regarding stem design and year of release were taken from manufacturer literature or one of two published implant atlases [2, 38], which allowed determination that these stems were first released for clinical use between 1983 and 2012. Several stems analyzed underwent evolutionary changes in their taper design and therefore can have one of two possible taper geometries depending on the year of manufacture [2]. Care was taken to identify the correct taper design in these cases from the laser etchings or markings on the trunnion.

A series of measurements were taken to the nearest 0.1 mm with a digital caliper (Neiko Tools, Ontario, CA, USA) to characterize the taper geometry of the femoral trunnion (Fig. 1), which we defined as the tapered male portion of the neck intended to engage the female taper of the femoral head. This device has a measurement accuracy of ± 0.02 mm. Measurements were taken by two independent observers (DAP and JLW). The intraclass correlation coefficient (ICC) [34], which measures reliability by comparing the variability of different ratings of the same entity with the total variation across all ratings and all entities, was selected to evaluate the reliability of the measurements between observations. The ICC for all measurements taken was greater than 0.90, where an ICC of 1.0 represents perfect agreement and 0.0 suggests that measurements are entirely random.

Flexural rigidity of the femoral trunnion was calculated according to Goldberg et al. [23]:

$$Flexural\,Rigidity = E \times I = E \times \left(\frac{\pi \times (ND)^4}{64}\right)$$

where E is the modulus of elasticity of the femoral neck alloy, I is the second (area) moment of inertia of the cross section about the bending axis associated with loading of the head of the femur, and ND is the neck diameter. The flexural rigidity describes how stiff or flexible the trunnion is in response to a bending moment. The second moment of area is a geometric property of the neck that describes the spread of the cross-sectional area away from the neutral axis of bending (typically an axis through the centroid, or geometric center).

The modulus of elasticity for each trunnion was taken from the literature for each material (Table 3) [17]. Because the moment of inertia is a variable of the ND at the point of contact of the femoral head, I was calculated at the geometric centroid z:

$$ND_z = D_1 - \frac{H_Z}{H}(D_1 - D_2)$$

where D_1 and D_2 represent the proximal and distal diameters of the trunnion (Fig. 1), H represents the measured height of the trunnion (Fig. 1), and H_z represents the location of the geometric centroid along the z-axis and was calculated by:

$$H_z = H \times \frac{D_1^2 + 2D_1D_2 + 3D_2^2}{4\left(D_1^2 + D_1D_2 + D_2^2\right)}$$

Additionally, to understand the contribution that various taper geometries have on flexural rigidity of the trunnion in isolation of the elastic modulus, a constant value for E was assumed, and the flexural rigidity of each taper design was recalculated from the mean measurements for D_1, D_2, and H taken with the calipers.

Statistical analysis was performed using descriptive statistics including median and range for the flexural rigidity of the various femoral trunnions. Pearson product moment correlation coefficients were calculated to assess for potential correlations between the year each stem was introduced to the market and the calculated flexural rigidity of the trunnion, and its length, its diameter at the centroid (ND_z), and its elastic modulus. In addition, a multiple linear regression analysis of significant variables was performed.

Results

The median flexural rigidity of the trunnion among all stems analyzed was 228 N-m^2. There was a wide range of

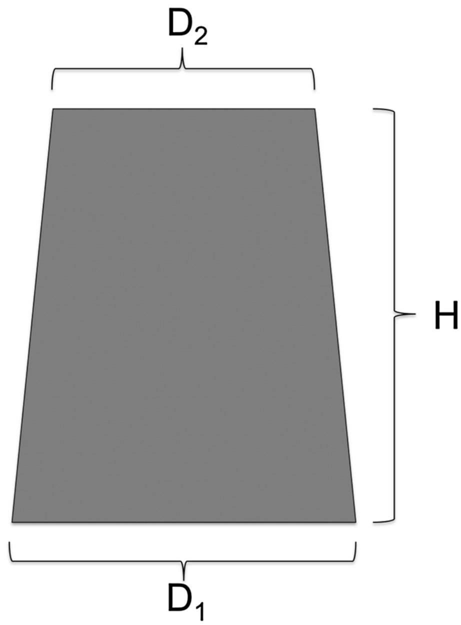

Fig. 1 This schematic diagram of a femoral trunnion depicts the three measurements H, D_1, and D_2 that were taken for each stem.

values among the various stems spanning nearly an order of magnitude (7.8x) between the most flexible (80 N-m^2) and the most rigid (623 N-m^2) femoral trunnions (Table 4). The three most flexible trunnions all shared the same base alloy (TMZF®) and taper geometry (V40™), as did the five most rigid trunnions (CoCr and 14/16, respectively).

When elastic modulus was assumed to be constant (elastic modulus of Ti6Al4V) to examine the effect of taper geometry in isolation, there was still a wide range of values among the various taper geometries, from 89 N-m^2 to 277 N-m^2 (Table 5). However, the magnitude of the difference between the most rigid and most flexible trunnions was smaller (3.1x) than in the previous analysis. The 14/16 taper design remained the most rigid, but there were three taper designs (10/12, 6°, and 11/13) that were more flexible than the V40™ taper design after controlling for the base alloy's elastic modulus.

There was a moderate negative correlation between trunnion length (−0.53; $p < 0.001$) and flexural rigidity (−0.23; $p = 0.04$) with time (Fig. 2), showing that, among the 85 revised and retrieved components that were evaluated, trunnions became shorter and less rigid as new stems were introduced in this group. In the multiple regression model, length and flexural rigidity were independently correlated with time (standardized coefficients $\beta = -0.51$ and $\beta = -0.17$, respectively). There was no statistically significant correlation observed between the release date of the stem and trunnion diameter ($p = 0.561$) or elastic modulus ($p = 0.123$).

Table 3. Modulus of elasticity of the alloys the 85 femoral stems included in the study

Alloy	Modulus *E* (GPa) [17]	Number
TMZF®	85	4
Ti-6Al-7Nb	110	2
Ti-6Al-4V	112	32
Orthinox® (316L)	210	1
CoCr	240	46

Discussion

Modularity at the head-neck junction of the femoral component has become a widely accepted design feature of THA. Corrosion at this modular junction was first described in the early 1980s [30] and has since been well documented in numerous retrieval analyses [10, 12, 13, 18, 28]. The underlying etiology for corrosion at this interface is multifactorial, but one of the strongest predictors of corrosion found at retrieval was the flexural rigidity of the femoral trunnion [23]. We therefore evaluated in a large retrieval database of 85 previously revised implant designs: (1) variability in flexural rigidity among different taper designs; (2) the contribution of taper geometry alone with respect to flexural rigidity of the femoral trunnion; and (3) temporal changes in flexural rigidity and taper length in this group. We found that (1) there is wide variability in the flexural rigidity among different taper designs, partly attributable to variability in the elastic modulus of the base alloy, but that (2) even when controlling for this factor, changes in taper geometry still accounted for large variability in flexural rigidity of the femoral trunnion. Finally, we noted (3) a significant temporal trend toward shorter and more flexible trunnions in our group of revised implants.

Our study has several limitations, the major being that it is based on an incomplete sample of femoral implants available in the United States during the past several decades rather than a complete collection, and thus our data may be subject to some degree of selection bias from the two institutions that housed the retrieval collections. Furthermore, the sample does not reflect use patterns of various implants across the country, because some of the devices were widely used for long periods, whereas others were used sporadically and with much less frequency. Although this incomplete sample is unlikely to substantially change our conclusion that there is wide variability in the flexural rigidity of various taper designs, it may affect the ability to accurately describe historical trends in trunnion evolution. Although we used a large number of different femoral designs from a wide range of manufacturers, this is an inherent weakness in the study design that

Table 4. Flexural rigidity of the trunnion in the 85 retrieved femoral stems sorted from most flexible to most rigid

Stem	Manufacturer	Taper	Alloy	Flexural rigidity (N-m²)
Accolade TMZF®	Stryker	V40™	TMZF®	80.06
Citation TMZF®	Stryker (Howmedica)	V40™	TMZF®	82.06
Meridian TMZF®	Stryker (Howmedica)	V40™	TMZF®	86.75
Harris-Galante Porous (HGP)	Zimmer	6°	Ti-6Al-4V	89.37
Bias Hip	Zimmer	6°	Ti-6Al-4V	94.88
Echo Bi-Metric	Biomet	Type I	Ti-6Al-4V	104.41
Uni-ROM	DePuy (J&J)	11/13	Ti-6Al-4V	108.22
Restoration Modular Revision	Stryker	V40™	Ti-6Al-4V	108.34
S-ROM	DePuy (JMP)	11/13	Ti-6Al-4V	108.98
OmniFlex	Stryker (Osteonics)	C-Taper	Ti-6Al-4V	116.38
Omnifit Titanium	Stryker (Osteonics)	C-Taper	Ti-6Al-4V	116.83
BiMetric	Biomet	Type I	Ti-6Al-4V	122.81
TaperLoc	Biomet	Type I	Ti-6Al-4V	122.90
Osteolock	Stryker (Howmedica)	PCA®	TMZF®	123.31
Integral	Biomet	Type I	Ti-6Al-4V	129.90
Emperion	S&N	12/14	Ti-6Al-4V	158.59
Anthology	S&N	12/14	Ti-6Al-4V	160.03
Wagner SL	Zimmer (Protek)	12/14	Ti-6Al-7Nb	160.12
Summit Tapered	DePuy	12/14	Ti-6Al-4V	160.54
Secur-Fit HA	Stryker (Osteonics)	C-Taper	Ti-6Al-4V	161.45
Tri-Lock	DePuy	12/14	Ti-6Al-4V	161.58
Secur-Fit Plus	Stryker (Osteonics)	C-Taper	Ti-6Al-4V	161.97
Corail	DePuy (Landos)	12/14	Ti-6Al-4V	162.25
Trabecular Metal Taper	Zimmer	12/14	Ti-6Al-4V	163.01
Perfecta RS Slim Neck	WMT (Orthomet)	12/14	Ti-6Al-4V	163.05
Synergy	S&N	12/14	Ti-6Al-4V	163.20
Profemur Z (Ti Neck)	WMT	12/14	Ti-6Al-4V	165.01
M/L Kinectiv	Zimmer	12/14	Ti-6Al-4V	165.32
M/L Taper	Zimmer	12/14	Ti-6Al-4V	167.47
ZMR Spout	Zimmer	12/14	Ti-6Al-4V	167.80
ZMR Calcar	Zimmer	12/14	Ti-6Al-4V	168.07
VerSys Fiber Metal Taper	Zimmer	12/14	Ti-6Al-4V	168.61
VerSys Fiber Metal MidCoat	Zimmer	12/14	Ti-6Al-4V	169.03
ZMR Cone	Zimmer	12/14	Ti-6Al-4V	169.66
CLS	Zimmer (Protek)	12/14	Ti-6Al-7Nb	174.57
Perfecta RS	WMT (Orthomet)	12/14	Ti-6Al-4V	181.08
Harris Precoat	Zimmer	6°	CoCr	185.51
Anatomic Cemented	Zimmer	6°	CoCr	185.94
LINK MP	WMT (LINK)	12/14	Ti-6Al-4V	187.62
BetaCone	WMT (LINK)	12/14	Ti-6Al-4V	190.23
PFC Cemented	DePuy (Codman)	10/12	CoCr	190.51
Exeter V40	Stryker (Howmedica)	V40™	Orthinox™	202.68
Rejuvenate	Stryker	V40™	CoCr	228.48
Accolade C	Stryker	V40™	CoCr	232.45
Citation AT	Stryker (Howmedica)	V40™	CoCr	247.84
Definition PM	Stryker (Howmedica)	V40™	CoCr	249.17
Omnifit C Stem	Stryker (Osteonics)	C-Taper	CoCr	256.23
Answer	Biomet	Type I	CoCr	259.31

Table 4. continued

Stem	Manufacturer	Taper	Alloy	Flexural rigidity (N-m^2)
Spectron EF 12/14	S&N (Richards)	12/14	CoCr	335.10
Replica	DePuy	12/14	CoCr	335.15
Echelon	S&N	12/14	CoCr	339.09
SMF	S&N	12/14	CoCr	340.23
Summit Cemented	DePuy	12/14	CoCr	340.54
Synergy Cemented	S&N	12/14	CoCr	342.87
Summit Basic Cemented	DePuy	12/14	CoCr	343.32
Redapt	S&N	12/14	CoCr	346.53
Advocate Cemented Stem	Zimmer	12/14	CoCr	351.10
Echelon Cemented	S&N	12/14	CoCr	353.07
VerSys Beaded Full Coat Plus	Zimmer	12/14	CoCr	355.69
Endurance	DePuy	12/14	CoCr	356.37
Solution 12/14	DePuy	12/14	CoCr	356.46
PCA	Stryker (Howmedica)	PCA®	CoCr	357.46
Excel Press-Fit	DePuy	12/14	CoCr	357.61
VerSys Cemented Revision	Zimmer	12/14	CoCr	357.73
Prodigy	DePuy	12/14	CoCr	358.04
Profemur Z (CoCr Neck)	WMT	12/14	CoCr	358.41
AML 12/14	DePuy	12/14	CoCr	358.93
Epoch	Zimmer	12/14	CoCr	359.51
VerSys Heritage	Zimmer	12/14	CoCr	359.90
VerSys Press-Fit LD/FX	Zimmer	12/14	CoCr	360.22
VerSys Cemented	Zimmer	12/14	CoCr	360.53
VerSys Beaded Midcoat	Zimmer	12/14	CoCr	362.27
Solutions Calcar Revision 12/14	DePuy	12/14	CoCr	363.04
VerSys Beaded Fullcoat	Zimmer	12/14	CoCr	363.11
VerSys Cemented LD/FX	Zimmer	12/14	CoCr	365.31
VerSys Beaded Full Coat Revision	Zimmer	12/14	CoCr	365.62
Ranawat-Burstein	Biomet	Type II	CoCr	377.19
Perfecta IMC	WMT (Orthomet)	12/14	CoCr	405.71
Extend Porous	WMT	12/14	CoCr	407.90
Perfecta PDA CoCr	WMT (Orthomet)	12/14	CoCr	418.19
Spectron EF 14/16	S&N (Richards)	14/16	CoCr	561.03
Solution 14/16	DePuy	14/16	CoCr	587.38
AML 14/16	DePuy	14/16	CoCr	598.28
CML	DePuy	14/16	CoCr	604.11
Solution Calcar Revision 14/16	DePuy	14/16	CoCr	623.20

could not be overcome based on the number of implants that we had available. Furthermore, additional sampling and selection bias may exist as the implants studied are all retrievals of revised components, and thus may represent a group of implants more prone to failure. We think this is a much smaller concern, as most of these were widely used implants, many with excellent track records, and were represented in our retrieval collection only because they were so commonly used. Finally, measurements were taken manually from retrieved components that had been implanted previously, thus leaving some room for measurement error, although the small degree to which these potential errors would affect our measurements is unlikely to jeopardize our larger conclusions.

Our study shows that femoral trunnions from different stem designs and different manufacturers exhibit a wide range of variability in flexural rigidity, related partly to taper geometry but also to the material properties of the base alloy. Stems with smaller taper geometries and those made from more flexible alloys have trunnions that offer

Table 5. Mean flexural rigidity and standard deviations of the various taper designs*

Taper design	Flexural rigidity (N-m^2)
10/12	88.9†
6°	89.4 ± 3.9
11/13	108.6 ± 0.5‡
V40™	110.2 ± 4.1
Type I	120.2 ± 9.5
C-Taper	135.2 ± 24.2
PCA® (2° 52′)	164.6 ± 3.1§
12/14	167.9 ± 8.9
Type II	176.0†
14/16	277.6 ± 10.7

* Assuming a constant modulus of elasticity (calculated for Ti-6Al-4V); †calculation based on one data point; ‡calculation based on two data points (108.2 and 109.0 N-m^2); §calculation based on two data points (162.5 and 166.8 N-m^2).

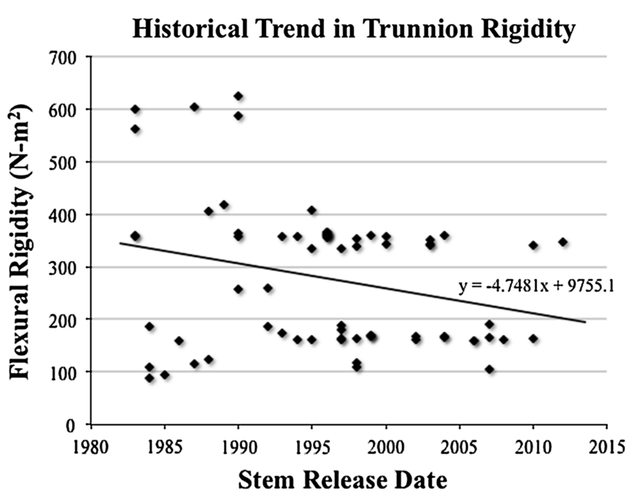

Fig. 2 The graphic representation shows how flexural rigidity diminished based on the release date of the stem.

less flexural rigidity than those with either a larger taper geometry or a stiffer material, which may be a risk factor for corrosion in some implant designs. Flexural rigidity is an important factor in inducing corrosion because it affects elastic-based micromotion (or fretting) that arises at the modular junction when applied loads or moments cause elastic strains. These strains generate stretching (on the tensile side) and compression (on the compressive side), causing displacements of approximately 5 to 40 μm [20], in line with observations of fretting scars [18].

When the elastic modulus was held constant across all taper geometries to examine only the effects of taper geometry on flexural rigidity, we found there was still substantial variability among the different designs. Early retrieval analyses were particularly concerning for the potential for corrosion with stems with a 6° taper [9, 10, 13], which is a small design with low flexural rigidity. This taper geometry was associated with some of the least rigid trunnions in our study (Tables 4, 5). Concerns regarding corrosion seen with this taper design were one of the major factors that pushed manufacturers to offer larger taper designs, thus decreasing the potential for corrosion at the head-neck junction and leading to near-universal adoption of modular femoral heads. Conversely to the best of our knowledge, there has been no reports of clinically relevant corrosion in association with a 14/16 taper, which was the most rigid taper design according to our calculations.

With the retrieval collection that we examined that spanned three decades of trunnion designs, we observed a modest but clear trend toward shorter and more flexible trunnions. Smaller trunnions offer potential advantages in that they can reduce the head-neck ratio and increase ROM to impingement, thereby decreasing postoperative instability [1, 33]. This trend toward more flexible taper designs may partly explain the apparent increasing frequency of taper corrosion seen in recent years. Since 2010, there have been multiple case reports [6, 11, 29, 31, 32, 39] and a larger case series [14, 15] documenting adverse local tissue reactions secondary to corrosion at the modular head-neck junction. Some of these reports [6, 11, 14, 29, 32] have identified a single taper design (V40™) in stems made from a flexible beta Ti alloy (TMZF®) that is approximately 30% less rigid than the more widely used Ti-6Al-4V. Similar cases associated with this type of implant have been reported in the FDA's Manufacturer and User Facility Device Experience database [36]. The combination of a small trunnion and lower modulus alloy results in this particular stem design offering the lowest flexural rigidity at the femoral trunnion of any of the 85 stems analyzed (Table 4) and may be a cause for concern. However, corrosion is a multifactorial process that depends not only on these mechanical causes, but also on other factors such as the method of manufacture and intraoperative assembly [3, 5, 16, 21, 26, 27].

Femoral trunnions exhibit wide variability in their flexural rigidity, attributable partly to their taper geometry and partly to the material properties of the base alloy. This wide range of flexural rigidity may help explain why some femoral stem designs may be associated with a greater incidence of corrosion and adverse local tissue reactions than other designs, although these complications are multifactorial and cannot be explained by this single variable in isolation.

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