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Review Article

Selecting a Press-fit Stem for Total Hip Arthroplasty: The Rationale and Evolution of the Modern Femoral Prosthesis

Michael Blankstein, MD, MSc, FRCSC

Mark A. Haimes, MD, MS

Nathaniel J. Nelms, MD, FAAOS

ABSTRACT

Noncemented press-fit femoral stems predominate in total hip arthroplasty for all age groups with generally excellent long-term survivorship. The 2021 American Joint Replacement Registry reports that 96% of all elective primary total hip arthroplasties used noncemented femoral implant fixation.[1] Today, there are many styles of press-fit stems, each with supposed benefits, based on a range of design philosophies. Design aspects to consider when selecting a stem are numerous, including stem geometry, stem length, collared or collarless, material properties, and surface structure. Although most stem designs demonstrate excellent results, the differences in stem designs are intimately linked to additional factors such as ease of use/implantation, percentage of surface osseointegration, overall bone removal versus bone stock preservation, subsequent femoral stress shielding, and consideration of complexity of later revision. A surgeon with a broad understanding and appreciation of femoral stem designs should be prepared to select between the multitude of options to best serve individual patients.

From the University of Vermont Medical Center, Orthopedics and Rehabilitation Center, and the Department of Orthopaedics and Rehabilitation, The Robert Larner, M.D., College of Medicine at The University of Vermont, Burlington, VT.

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Over the past 40 years, femoral prosthesis design has steadily advanced. Although it is difficult to generalize for all implant manufacturers, there has been an overall pattern in the progression of stem design. First-generation femoral stems were predominately longer cobalt-chromium stems that obtained more distal meta-diaphyseal fixation using a distal cylindrical design. The implants often had more extensive coating, allowing for a large area of biologic osseointegration. Introduced at the same time, some first-generation titanium alloy stems were not circumferentially porous-coated and had high failure rates. Second-generation noncemented femoral implants were designed to provide more reliable long-term fixation while limiting osteolysis by incorporating circumferential proximal ingrowth surfaces.[2] Despite the excellent survivorship of these stems, concerns for thigh pain and proximal stress shielding led to modification of these stems to promote primarily proximal metaphyseal fixation with some stems becoming fluted distally. Furthermore, different surface

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materials, metals, and stem geometries were explored. Improvements in metal surface preparations such as grit blasting, sintering of beads, and plasma spraying today produce reliable stem osseointegration. The third-generation proximally porous-coated, metaphyseal engaging, ream-and-broach or "fit-and-fill" tapered titanium alloy stems have shown a survivorship of 99.5% at a minimum 15-year follow-up.[3] In an effort to preserve bone stock for possible future revisions, shorter smaller stems have been developed with varying success. Various taper geometries have also been considered, and reduced lateral shoulder/trochanter-sparing designs have evolved. Common modern stems include dual tapers, triple tapers, and tapered wedge/blade stems. The single-wedge tapered stems only taper and extract the bone in the medial-to-lateral plane (M/L) while double-wedge tapered stems extract the bone in the anterior-to-posterior plane (A/P) as well. A recent systematic review concluded that noncemented femoral implants with single-wedge and double-wedge geometries are associated with a markedly higher risk of periprosthetic femoral fractures.[4] The compaction broaching technique was introduced for bone preparation. Early on, this technique demonstrated increased fixation stiffness up to 6 weeks[5]; however, there is an increased fracture rate in cadaver studies[6] and intraoperative fractures in vivo.[7] Owing to evidence of increased micromotion in the coronal plane with medial/lateral translation and varus/valgus angulation,[8] new broaching techniques were developed. Recently, as the popularity of the anterior approach has risen, shorter compaction broaching curved stems have come to the market with great success. These hybrid rasp-impaction broaching stems extract the bone in the M/L plane but compact the bone in the A/P plane. Our review will explore the various aspects of noncemented femoral stem design in detail.

Biology of Noncemented Fixation

Noncemented stem fixation is achieved by an initial press-fit with mechanical stability of the stem in the bone, but long-term survivorship of press-fit implants relies on achieving osseointegration. Osseointegration was first described in dentistry by Branemark as a direct connection between a load-bearing implant and a living organized bone.[9] Osseointegration is achieved through a process similar to fracture healing, which is affected by implant material, geometry, surface characteristics, and coatings. Preparing the femoral canal creates local bone trauma, followed by a healing response that progresses from a clot to a complex fibrous matrix. The matrix becomes calcified, is converted to a woven bone, and is ultimately remodeled to a lamellar bone in intimate contact on the implant surface. This process occurs with early bone trabecula beginning biologic fixation as early as 10 to 14 days after implantation, followed by a mixture of more mature woven and lamellar bone present at 3 months, followed by several months of remodeling. For this healing to result in successful osseointegration, implant micromotion must be limited. Less than 20 μm of motion results in primarily bone formation along the implant, whereas greater than 150 μm will produce mostly fibrous tissue growth.[10]

Surface Engineering

Materials and Fixation

Implant surface characteristics determine whether osseointegration will result in bone ongrowth or ingrowth to a femoral stem. Ongrowth is achieved by bone adhesion to a roughened implant surface, whereas ingrowth requires a porous surface design to allow the bone to integrate into the surface pores. Implant surface modifications to allow osseointegration can generally be classified as physical, chemical, and biological, but physical modifications to the stem surface are most used. Two common techniques to create a titanium ongrowth stem surface are grit blasting and plasma spraying. Grit blasting is a prototypical physical surface modification in which abrasive particles are used to roughen the surface in a process similar to sandblasting. Plasma spraying is another physical technique whereby molten metal is applied by a plasma torch to the implant. This metal surface deposition produces a textured surface known to enhance biologic fixation. Ingrowth surfaces are often created by sintering beads. This process involves the application of tiny metallic beads, which are stabilized to the stem surface by a heat treatment. It is important that porous coatings are circumferential because interruption in the porous coating is associated with loosening and failure.[11]

Stem ingrowth surfaces are designed to create optimal pores for bone incorporation. Although ingrowth surfaces are most often created by sintering beads, other processes more commonly applied to acetabular implant surface manufacturing can be used such as chemical vapor deposition or additive manufacturing (3D printing) through processes of selective laser melting or electron beam melting. Porous tantalum has also been applied to femoral stems with successful ingrowth.

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Ingrowth surfaces require at least 100 μm pores for ingrowth, with larger pores greater than 200 μm necessary for intrapore capillary growth.[12] There is evidence that improved fixation may be achieved with 500 to 600-μm pores, but larger pores will prevent effective mechanical ingrowth.[13,14] Additional factors important for bone ingrowth into surface pores are pore interconnectivity, which enhances ingrowth, and pore geometry, of which the effects are less understood.

Hydroxyapatite Coatings

Hydroxyapatite (HA) is an inorganic mineral with a similar structure to that of the bone. HA and other related bioactive calcium phosphate coatings have osteoconductive properties. These implant coatings have been used since the mid-1980s.[15] Although HA coatings on femoral stems are not directly associated with improved survivorship, there are compelling benefits to HA-coated femoral stems. One series found decreased thigh and trochanteric pain in stems with HA coatings.[16] HA-coated stems have been associated with improved filling of bone gaps, prevention of distal stem osteolysis, and improved osseointegration on retrieval studies.[17] At the long-term follow-up, HA-coated femoral stems have displayed improved Harris hip scores.[18] Despite the clearly recognized benefits of HA coatings, there is a potential for HA delamination and third-body wear if not optimally applied. Appropriate HA-coating thickness and purity are clinically associated with a decreased incidence of thigh pain.

Metallurgy

Modern hip stems are designed specifically for either noncemented or cemented bone fixation. Cemented femoral stems are typically composed of stainless steel or cobalt-chromium (CoCr) alloy. Titanium alloy stems have been used with cement fixation, but this application is controversial because of concerns of micromotion with cement debonding related to the relatively low elastic modulus of titanium.[19]

Press-fit stems are usually manufactured with alloys of titanium or CoCr. Cobalt-chromium is a stiff material with a high Young modulus such that it is particularly associated with stress shielding and proximal femoral bone loss, whereas titanium has a Young modulus closer to that of cortical bone with a less potential for stress shielding.[20] Cobalt-chromium alloy is used in the manufacturing of fully porous-coated stems. In these stems, cobalt-chromium beads are sintered to the surface over most of the length of the stem. This process weakens the implant material properties, but the risk of stem fracture is manageable because of the inherent strength of CoCr. CoCr alloys used in femoral stems typically contain about 64% cobalt and 28% chromium. The cobalt adds strength while the chromium contributes to corrosion resistance by forming a surface oxide. CoCr alloys are inherently less biocompatible than titanium alloys and contain smaller amounts of molybdenum, nickel, aluminum, manganese, iron, and lanthanum.[12] Titanium is the most important and common material used for hip stems today. It has a high potential for osseointegration, is biocompatible, is inherently corrosion resistant, is abundant, and is relatively inexpensive.[21] Titanium stems exist in a variety of formats, but fully porous-coated designs with sintered beads are not available because the sintering process weakens the implant to such a degree that stem fracture would be a concern. Commercially pure titanium is used for implant manufacturing, but most femoral stems are produced from a titanium alloy. Although there are many possible clinically useful titanium alloys, the primary alloy is $Ti_6A_{l4}V$, which contains 6% aluminum and 4% vanadium. The addition of these elements to titanium brings the elastic modulus closer to that of the bone with increased implant strength provided by the addition of aluminum and improved corrosion resistance provided by including vanadium.[12] Titanium-molybdenum-zirconium-iron alloy (TMZF, Stryker Orthopaedics), an alternative titanium alloy previously manufactured, has been associated with significant mechanically assisted corrosion at the taper junction when used with large CoCr femoral heads with the high-offset stem and increased neck lengths[22] (Figure 1).

Geometry and Design Classification

A classification system for noncemented femoral stems was developed in 2011 and did not originally include short stems.[23] There is no clear definition or universal classification system for short stems. Proposed definitions include less than 120 mm in length[24] or the tip of the stem being proximal to the metaphyseal-diaphyseal junction.[25] A classification system was created for short stems based on the level of neck resection: neck retaining versus neck sparing versus neck harming[26] (Figure 2). Another classification was based on the level of fixation: metaphyseal stabilized, neck stabilized, and head stabilized.[25] The noncemented femoral stem classification was addended to a descriptive classification which included short stems in 2014 and updated to a comprehensive system in 2020 as part of a current concepts review[24] (Table 1). Ultra-short and short stems (Type 1) are subdivided into Types 1A, 1B, 1C, and 1D (Table 2).

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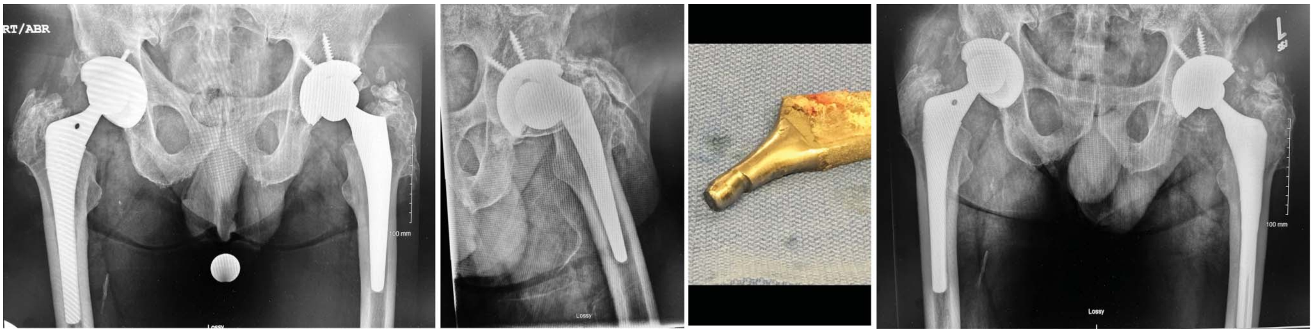
Figure 1



Radiographs and image showing gross trunnion failure due to mechanically assisted crevice corrosion of the LFIT CoCr femoral head and the Accolade titanium-molybdenum-zirconium-iron alloy femoral stems (TMZF). This patient was revised with a fit-and-fill conventional primary metaphyseal bearing stem. This case illustrates the importance of stem metallurgy, the trunnion, ease of revision from a blade stem with minimal bone loss, and being able to use a more robust, yet primary stem for a revision which does not completely rely on diaphyseal fixation. CoCr = cobalt chromium, LFIT = Low Friction Ion Treatment

These include stems that rely on femoral neck fixation, calcar loading, calcar loading with lateral flare, and shortened tapered stems, respectively. The full length stems include Types 2 through 7. These include single-wedge, double-wedge, gradual taper with meta-diaphyseal filling, diaphyseal-engaging, modular, and anatomic. This classification system allows orthopaedic surgeons to categorize the options for noncemented femoral stems.

One distinction in the classification is the subdivision of Type 6: modular stems into those with a modular neck and modular body (Figure 3). The stems with a modular body (metaphyseal sleeve) have demonstrated a relatively good track record while allowing the patient specific implant anteversion adjustment for those with dysplasia.[28] However, the modular neck prosthesis is associated with early implant failure.[29] Owing to failures and complications related to the neck-stem interface, including eccentric loading, fretting, corrosion, fracture, and dissociation, certain prostheses with modular neck designs have been recalled.[29] Therefore, the authors recommend against the use of a prosthesis with a modular neck.

Figure 2

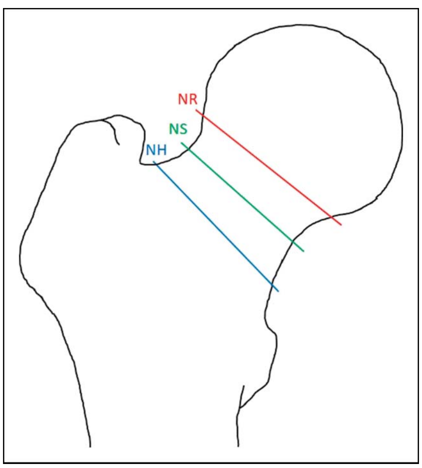


Illustration showing the classification of a short-stem femoral prosthesis by neck resection. NH = neck harming, NR = neck retaining, NS = neck sparing

Short Stems

The analysis of short-stem survivorship requires careful attention in reviewing the literature because there is no universal definition for short stems. Using a classification system and reviewing the surgical technique guides for each stem helps classify and compare stems from different companies. The two reviews by Khanuja et al and Kheir et al give a good general analysis and demonstrate the limited data and extensive variety of these stems.[24,27] For the purposes of this review, we define "short stems" as Type 1D.

Modern stem geometric design has focused on enhancing metaphyseal fixation through improving the medial curvature at the calcar and by tapering the lateral shoulder to preserve the greater trochanter. This also allows for easier bone preparation with minimally invasive techniques such as anterior approach total hip arthroplasty (THA).[30] The increased popularity of the anterior approach has led to shorter curved stem designs that are less prone to varus malposition.[31]

Overall, these stems show no difference in outcomes compared with longer stems. However, when reviewing specific comparisons of stems from the same company, there may be a difference in outcomes. Taperloc Microplasty (Zimmer) has demonstrated a markedly higher fracture risk when compared with Taperloc (Zimmer)

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Table 1. **Illustration of Examples of Noncemented Femoral Stems From the Updated Classification System**

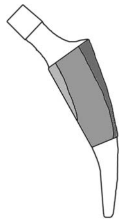
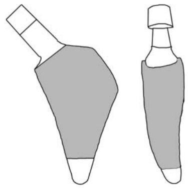
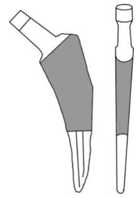
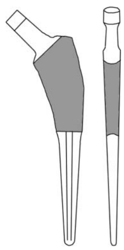
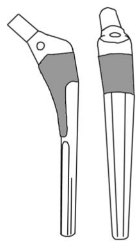
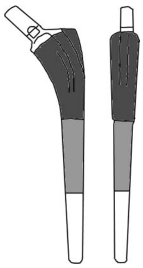
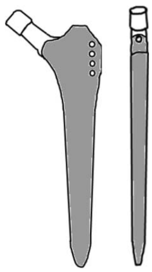
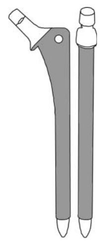
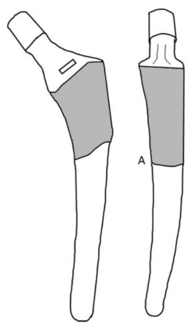
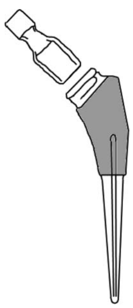
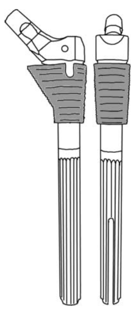
Short Stems			
Type 1: Short and ultra-short stems			
Type 1A: Femoral neck 	Type 1B: Calcar loading 	Type 1C: Calcar loading with lateral flare 	Type 1D: Shortened tapered stem 
Full-length Stems			
Type 2: Single-wedge 		Type 3: Double-wedge 	
Type 4: Gradual taper, metadiaphyseal filling		Type 5: Diaphyseal-engaging	
Type 4A: Tapered round 	Type 4B: Tapered rectangle 	Type 5A: Tapered spline/cone 	Type 5B: Cylindrical fully coated 
Type 6: Modular		Type 7: Anatomic 	
Type 6A: Modular neck 	Type 6B: Modular body 		

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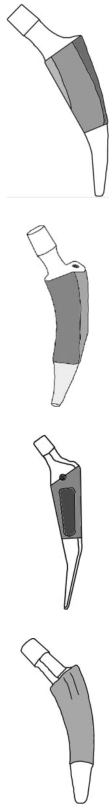
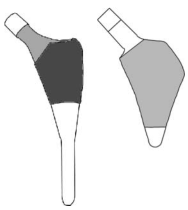
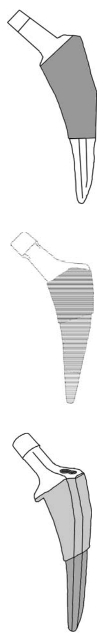
Table 2. Illustration of Examples of Short Noncemented Femoral Stems

Type 1: Short and ultra-short stems	
Type 1A: Femoral neck 	Type 1B: Calcar loading 
Type 1C: Calcar loading with a lateral flare 	Type 1D: Shortened tapered stem 

during a retrospective review of 851 hips.[32] Wagner conducted a prospective analysis of 517 consecutive THAs with mid-term follow-up on a newer short stem with a decreased lateral shoulder. The MonoconMIS (Falcon Medical) had a 96.1% survival rate at a mean follow-up of 5.3 years with relatively high rates of aseptic loosening.[33] The relatively newer short tapered stem Actis (DePuy) was compared with the fully HA-coated stem Corail (DePuy) in a retrospective cohort study of 330 THAs using the direct anterior approach. It should be noted that the Corail stem (DePuy) is difficult to classify because it has a proximal trapezoidal shape and distal quadrangular shape but is best classified as a dual wedge based on its taper in both the M/L and A/P planes. This study demonstrated no difference in the complication rate or patient-reported outcomes. No complications were reported for the Actis group; however, there was too small of a sample to demonstrate a statistically significant difference.[34]

Ultra-short Stems

Over time it was realized that with good metaphyseal fixation, stem extension into the diaphysis could be avoided with the benefit of bone preservation and potentially simplified future revision surgery. Based on this principle, ultra-short stems were designed. However, not all short stems achieve initial stability in the same region of the bone. When referring to ultra-short stems in the literature, the authors generally are referring to Type 1A-C stems.

Lidder et al conducted a systematic review of short metaphyseal loading stems including 28 studies and 5,322 hips. These showed similar survivorship when compared with conventional stems; however, there was a variety of stem designs, including both short and ultra-short designs, and no long-term follow-up.[35] This demonstrates the need to pay careful attention to the specific stem designs when reviewing the literature. A randomized controlled trial of 53 patients comparing the MiniHip (Corin) versus MetaFix (Corin) demonstrated less subsidence in the ultra-short stem with no notable difference in the dynamically inducible micromotion, complications, or functional outcome.[36] Zimmerer et al[37] compared 55 patients and matched control subjects with Nanos (Smith & Nephew) versus Corail (DePuy) and found no difference in patient-reported outcomes at 8 years with no revisions. Kim[38] reviewed multiple studies demonstrating the excellent survivorship of Proxima (DePuy) and good results with SMF (Smith & Nephew). A systematic

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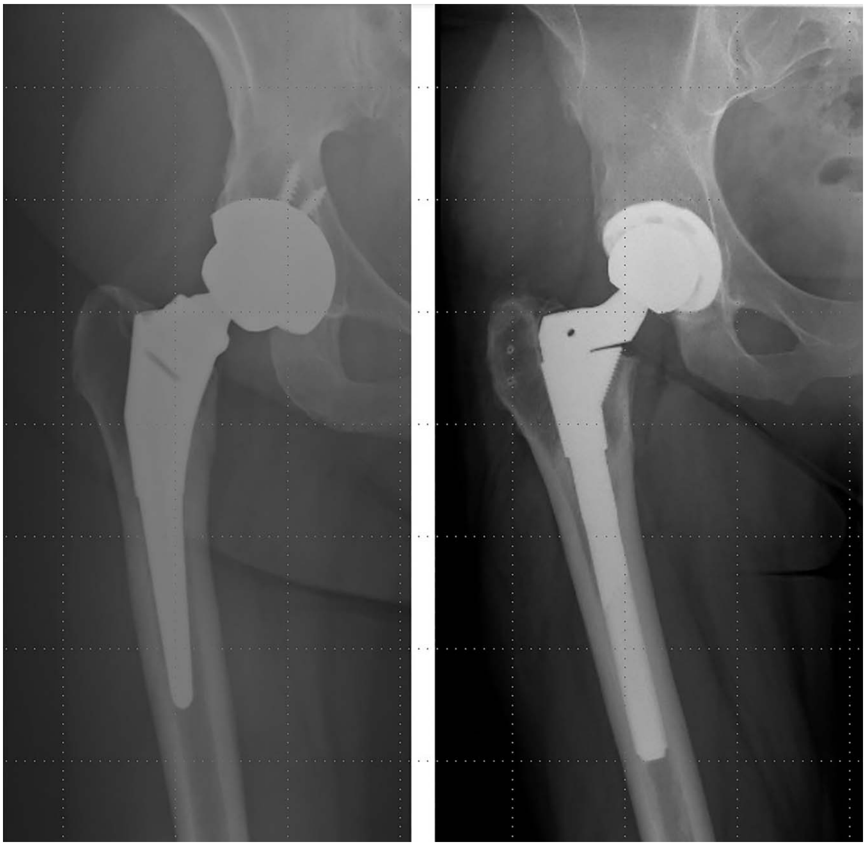
Figure 3



(Left) AP hip radiograph of a 75-year-old woman who received a right total hip arthroplasty using a femoral prosthesis with a modular neck. (Right) AP hip radiograph of a 36-year-old woman with history of hip dysplasia who received a right total hip arthroplasty. Her hip dysplasia was treated with a modular stem to allow for the proper anteversion of the femoral implant.

review including 56 cohorts in 52 studies divided femoral stems into neck retaining, neck sparing, and neck harming. They found a similar low revision rate for neck sparing and neck harming. The neck retaining prosthesis had a higher revision rate.[39]

The short tapered stems (Type 1D) seem to be a safe alternative to longer stems and allow for easier implantation during the anterior approach while preserving the bone for revision surgery and possibly decreasing cases of thigh pain (Figure 4). The combination of other factors mentioned in this review including surface materials, stem design, and broaching techniques need to be considered to avoid confounding when comparing these newer short, tapered stems to their predecessors or to each other. The ultra-short stems (Type 1A-C) tend to have less predictable outcomes because of more variable design philosophies such as location of fixation, level of neck resection, or cross-sectional shape.

The authors caution the use of Type 1A stems (femoral neck fixation) because of an increased risk of complications and lack of long-term outcomes. Type 1B (calcar loading) and Type 1C (calcar loading with lateral flare) stems show promising results; however, stem design differs markedly between different companies. Surgeons should cautiously consider the use of newer implants in this category without notable data on the outcomes.[24] Type 1D stems (shortened tapered) have become more prevalent in conjunction with increased popularity of the anterior approach.

Collared versus Collarless

The use of collared versus collarless noncemented femoral stems remains controversial with strong proponents on either side. The absence of a collar may allow some minimal early subsidence and additional prosthesis wedging within the bone. Such slight stem subsidence with a collarless prosthesis could theoretically contribute to improved ingrowth. The addition of a collar may not allow a stem to settle resulting in aseptic loosening. On the other hand, a collared stem may reduce subsidence, create compressive calcar loads, provide better primary axial and rotational/torsional stability, and might be protective against calcar fracture propagation and periprosthetic

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Figure 4

AP hip radiograph of a 56-year-old man who is 3 years postoperative from a right total hip arthroplasty using a fit-and-fill femoral prosthesis. He presented with a 2.5-year history of mechanical lateral thigh pain that was worse with activity due to erosion into the lateral cortex. Bone scan demonstrated increased uptake.

fractures. This may also prevent stress shielding by loading the calcar region. Regardless of the use of a collar, immediate stem stability promotes bony ingrowth.

Sershon et al[40] observed markedly lower periprosthetic fracture rates with collared and fit-and-fill (vs single-wedge) stem designs in patients of female sex, body mass index < 25, and age older than 65 years. A recent systematic review and indirect meta-analysis specifically evaluating femoral stem implantation using the direct anterior approach concluded that collared femoral stems and long femoral stems had decreased complication rates when compared with collarless and short femoral stems, although there were no differences in revision rates.[41] Furthermore, a registry study of 337,647 primary THAs from the UK National Joint Registry demonstrated that collars are protective against early periprosthetic femoral fractures around noncemented femoral implants.[42] As a result, numerous companies now offer femoral stems with a collared option. One may especially consider using a collared stem when relying on press-fit fixation in the osteoporotic bone.

Trunnion

The femoral stem taper or trunnion is a key design feature needed for a modular junction with the femoral head. The stem taper junction allows intraoperative adjustment and fine-tuning of leg length and offset. There are multiple taper geometries of varying lengths, taper angles, and surface preparations on the market. Over recent years, taper designs have faced increased scrutiny due to the recognition of adverse tissue reactions to metal debris released from the taper-head junction.[43] Trunnion surface preparation may be smooth or grooved. In vitro testing suggests that a smooth trunnion may produce less volumetric wear.[44] Grooved trunnion surfaces are designed though to theoretically reduce stress concentration on affected ceramic heads (Figure 5). Shorter trunnions have been associated with increased wear.[45] Because individual implant manufacturers have specific taper manufacturing specifications, there are more than 30 unique femoral stem taper geometries.[46] Even common tapers of the same name (eg, 12/14) have somewhat different geometries between companies. For this reason, it is important that only femoral heads provided by the stem manufacturer are used to prevent modular junction failure.

Choosing the Stem for Your Patient

In the setting of multiple available femoral implants with similar longevity, it is important for an orthopaedic surgeon to choose a stem that fits the patient's needs while considering their preferred stem design philosophy, experience, and familiarity with the implant. A recent interesting study from the National Joint Registry (NJR), included 764,888 primary THAs conducted by 3,213 surgeons between 2008 and 2017. One-hundred eleven THA consultant surgeons (3.5%) were found to be potential revision outliers, meaning they were more likely than nonoutlier surgeons to have their primary arthroplasty procedures revised. Surgeons who used more types of implants had increased odds of being an outlier.[47]

In every surgeon's armamentarium, there should be at least three femoral stems: a modern noncemented stem to be used for routine primary total hip arthroplasties with normal femoral anatomy; a cemented stem for osteoporotic/pathologic bone; and a diaphyseal bearing

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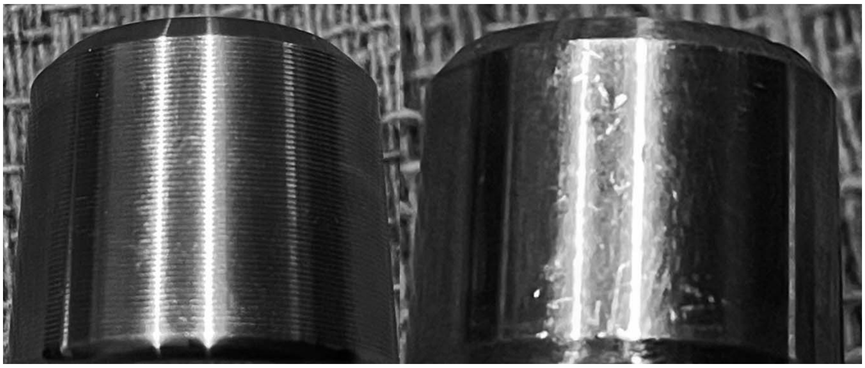
Figure 5

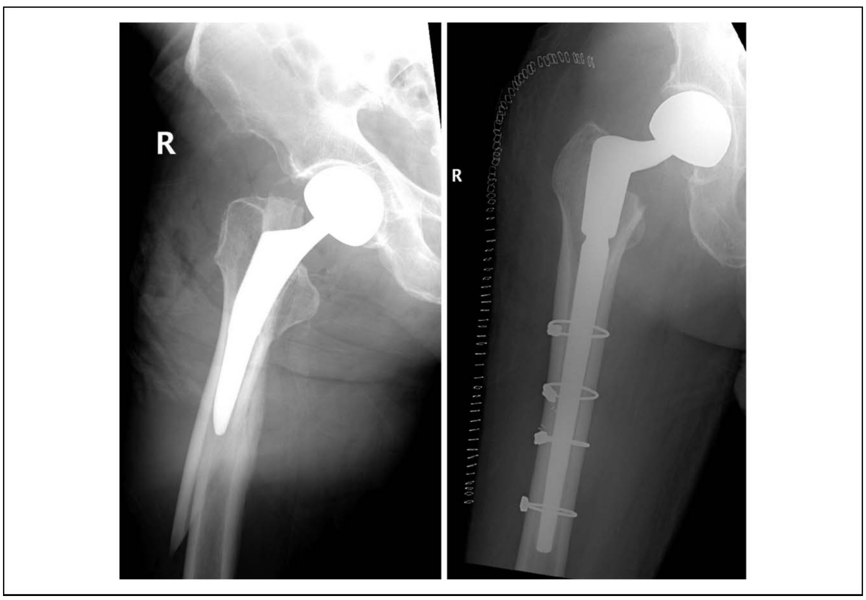


Photograph of a grooved trunnion on the left and a smooth trunnion on the right.

stem for complex primary arthroplasties, abnormal femoral anatomy, conversions, revisions, and periprosthetic fractures. Many diaphyseal bearing stems are also modular, which allows adjustment of stem anteversion, offset, and length in the setting of abnormal proximal femoral anatomy. Figure 6 illustrates the importance of the orthopaedic surgeon's familiarity with a cemented stem and a diaphyseal engaging stem. This is highlighted in the American Academy of Orthopaedic Surgeons Clinical Practice Guidelines with a recent update to a strong recommendation supporting the use of cemented femoral stems in patients undergoing arthroplasty for femoral neck fractures.[48] Moreover, if a surgeon routinely uses a blade or a short stem, there might be a role for a longer fit-and-fill type stem for certain primaries or conversion arthroplasties in which a revision diaphyseal engaging stem is not necessary (Figure 7). In a recent study, the use of noncemented tapered wedge stems in patients with Dorr A femurs demonstrated a higher risk of periprosthetic fracture and aseptic loosening.[49] Hence, one may consider using a fit-and-fill stem or a ream-and-broach stem in these cases to turn a Dorr A femur into a Dorr A/B.

Our goal was to achieve predictable biologic femoral implant fixation and long-term osseointegration with low rates of periprosthetic fractures and aseptic loosening. Meanwhile, if the stem needs to be removed, ideally it could be done in a fashion that preserves bone stock for

Figure 6



Preoperative and postoperative radiographs of an 86-year-old man who was treated for a femoral neck fracture with a press-fit hemiarthroplasty. He sustained a periprosthetic fracture 2 weeks postoperatively and was treated with a revision to a diaphyseal bearing modular fluted tapered stem.

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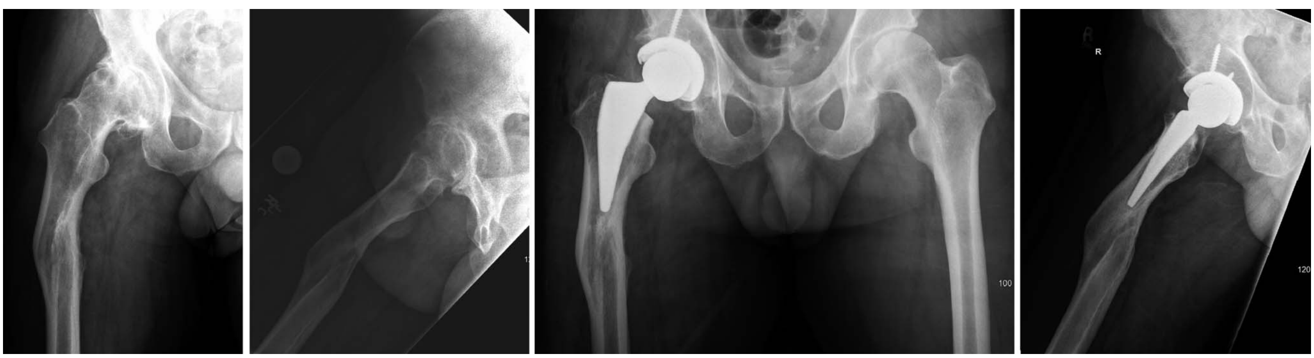
Figure 7

Preoperative and postoperative radiographs of a two different conversion arthroplasties each using a fit-and-fill stem without the need for a diaphyseal bearing revision stem.

future revision surgery. Considering all the factors mentioned earlier, numerous variables should be deliberated: stem subsidence, stress shielding, bone preservation, survivorship, thigh pain, periprosthetic fracture risk, trunnion designs, revision issues, and ease of use related to minimally invasive approaches. The authors recognize that most of the modern noncemented stems work very well and have excellent survivorship. The surgeon must know the nuances of each system, and preoperative templating is paramount. Although some stems can essentially be used in almost all cases, there are circumstances where one might consider a different design, such as in cases with

Figure 8



Preoperative and postoperative radiographs of a patient with a proximal femoral deformity from a previous fracture malunion treated with a short stem. The use of a traditional stem would not be possible here without an osteotomy.

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previous implant or deformity (Figure 8). In some instances, longer fit-and-fill stems are useful with distinct femoral anatomy, such as significant metadiaphyseal mismatch, extreme champagne flute femur with a tight canal, or posttraumatic conversion cases (Figure 7).

Summary

Femoral stems have evolved in their metals, surface modifications, fixation, geometry, and length. Titanium has emerged as the most used metal alloy that achieves robust bone ongrowth or ingrowth using a variety of implant surface modifications. Femoral stem design geometry today has improved metaphyseal fixation allowing shorter stems with trochanteric-sparing designs. Since the introduction of noncemented femoral stems, continual improvements have been achieved and more can be expected in the future.

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