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Short single-wedge stems have higher risk of periprosthetic fracture than other cementless stem designs in Dorr type A femurs: a finite element analysis

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Abstract

Background: The use of total hip arthroplasty (THA) femoral stems that transmit force in a favourable manner to the femur may minimise periprosthetic fractures. Finite element analysis (FEA) is a computerised method that analyses the effect of forces applied to a structure with complex shape. Our aim was to apply FEA to compare primary THA cementless stem designs and their association with periprosthetic fracture risk.

Methods: 3-dimensional (3D) models of a Dorr Type A femur and 5 commonly used primary THA cementless stem designs (short single wedge, standard-length single wedge, modular, double-wedge metaphyseal filling, and cylindrical fully coated) were developed using computed tomography (CT) imaging. Implant insertion, single-leg stance, and twisting with a planted foot were simulated. FEA was performed, and maximum femoral strain along the implant-bone interface recorded.

Results: Femoral strain was highest with short single-wedge stem design (0.3850) and lowest with standard-length single-wedge design (0.0520). Location of maximum femoral strain varied by stem design, but not with implant insertion, single-leg stance, or twisting with a planted foot. Strain was as high during implant insertion as with single-leg stance or twisting with a planted foot.

Conclusions: Our results suggest the risk of intraoperative and postoperative periprosthetic fracture with THA in a Dorr A femur is highest with short single-wedge stems and lowest with standard-length single-wedge stems. Consideration may be given to minimising the use of short single-wedge stems in THA. Implant-specific sites of highest strain should be carefully inspected for fracture.

Keywords

Femur, finite element analysis, periprosthetic fracture, stem, total hip arthroplasty

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Introduction

Revision total hip arthroplasty (THA) has a high rate of patient morbidity, particularly when reoperation occurs in the acute postoperative period, and is costly to the health-care system.[1] The number of THA revision surgeries is increasing at a rate faster than that of primary THA.[2]

Over 21 years the Mayo Clinic reported periprosthetic femur fracture following primary THA with cemented and cementless stems occur at rates of 0.6% and 0.4%,

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respectively.[3] Advanced age, obesity, and osteoporosis are associated with a higher risk of periprosthetic femur fracture.[4,5] Of all periprosthetic femur fracture patients, 63.1% have a postoperative complication, 54.9% receive a blood transfusion, 7.8% require reoperation, and 2.7% die within 30 days.[6] The cost of periprosthetic femur fracture is not only dire for the patient, but also significant to the healthcare system at $26,522 to $36,161 for the initial hospitalisation.[7]

By minimising periprosthetic fractures following THA, the number of revision surgeries may be decreased. THA femoral stems differ in geometry, thus load applied through stems has varying effects on surrounding bone. Use of a THA femoral stem design that transmits force in a favourable manner to the femur may minimise the likelihood of intraoperative, as well as postoperative, periprosthetic fracture.[8–10]

Finite element analysis (FEA) is a computational technique used in the field of engineering to evaluate the effect of forces applied to a structure with a complex shape by dividing it into smaller, simple shapes. Advantages of FEA are that it allows evaluation of a structure with dissimilar properties, such as the femur comprised of cortical and cancellous bone, and discrimination between local effects, such as those observed at the medial versus lateral proximal femur. FEA is also not compromised by variation in bone quality between specimens. Primary stability and stress shielding of a select few, mostly esoteric, THA femoral stem designs have been investigated using FEA.[11–16] To our knowledge, FEA has not previously been utilised to study the more clinically impactful issue of periprosthetic fracture risk as it varies widely across implanted femoral stem designs.

The aim of this study was to use FEA to evaluate which of the most commonly utilised primary THA cementless stem designs is associated with the lowest risk of intraoperative and postoperative periprosthetic femur fracture.

Material and methods

Development of 3D femur model

A 3-dimensional (3D) femur model was developed using 1 mm-thick computed tomography (CT) scan slices of a human male Dorr Type A femur. CT images were imported into Materialise Mimics Innovation Suite (Materialise NV; Leuven, Belgium), image processing software that allows 3D reconstruction from 2-dimensional (2D) CT images. Using the relative difference in Hounsfield units between soft tissue and bone, cortical and cancellous bone were highlighted and isolated (Figure 1).

The 3D model was imported into Geomagic engineering software (3D Systems; Rock Hill, South Carolina), and smoothed to reduce surface projections and anomalies. The model was then sectioned 50 mm proximal to the medial and lateral epicondyles of the distal femur.

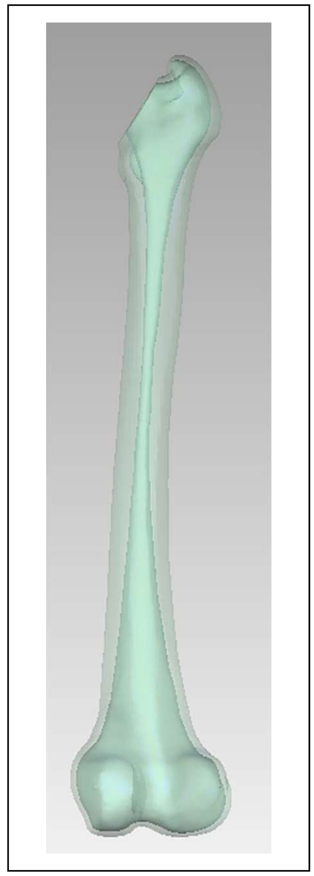

Figure 1. 3D femur model is presented with representation of cortical and cancellous bone.

Development of 3D femoral stem models

3D models of five commonly utilised primary THA cementless stem designs were developed using the protocol above. 5 femoral stems from a single manufacturer (Smith and Nephew; London, UK) were utilised, each of a different design type as classified by Khanuja et al.:[17] Short Titanium Stem (short single wedge, titanium alloy), Anthology (standard-length single wedge, titanium alloy), Emperion (modular, titanium alloy), Synergy (double wedge metaphyseal filling, titanium alloy), and Echelon Primary (cylindrical fully coated, cobalt-chrome alloy). 0.5 mm-thick CT scan slices of each femoral stem were used to accurately capture implant geometry inclusive of coating, and metal artifact was filtered.

Sizing and positioning of femoral stems

A femoral neck osteotomy 1.0 cm proximal to the lesser trochanter was simulated in Geomagic to prepare the femur for femoral stem insertion. A board-certified, fellowship-trained adult reconstruction surgeon determined sizing and positioning of each femoral stem model within the femur model according to standard operative technique

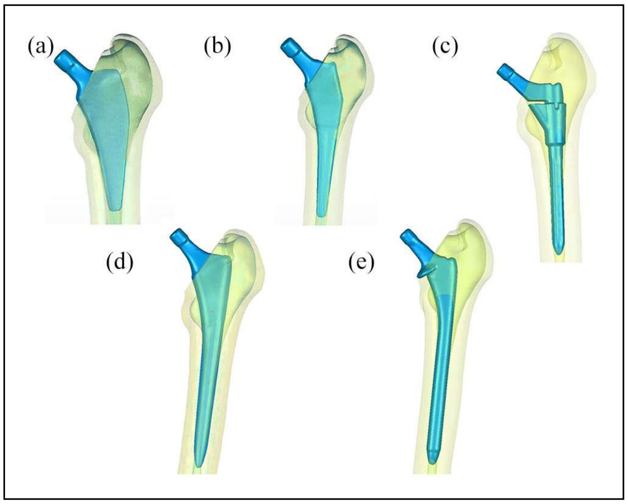

Figure 2. (a) Short single-wedge (b) Standard-length single-wedge (c) Modular (d) Double-wedge metaphyseal filling (e) Cylindrical fully-coated stem models fit into femur model.

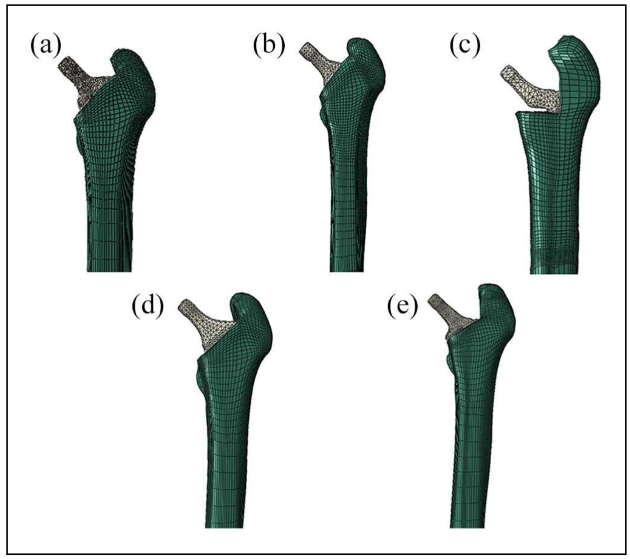

Figure 3. Femoral stems are meshed with tetrahedral elements and femur is meshed with hexahedral elements for FEA. (a) Short single-wedge (b) Standard-length single-wedge (c) Modular (d) Double-wedge metaphyseal filling, and (e) Cylindrical fully-coated stems.

(Figure 2). Following implant placement against cortical bone, calcar planing was simulated by orienting the femoral neck osteotomy parallel to the proximal boundary of stem porous coating.

Finite element analysis

The femoral stems were meshed with tetrahedral elements using HyperMesh (Altair Engineering; Troy, MI, USA), while the femur was meshed with hexahedral elements using IA-FEMesh (CCAD; University of Iowa) (Figure 3). FEA was performed using the Abaqus FEA software package (SIMULIA; Providence, Rhode Island). Both our group and others have previously established the validity of this FEA model as it was found to reproduce both *in vitro* and *in vivo* experimental findings.[18,19]

Simulation of implant insertion, single-leg stance, and twisting with planted foot

Intraoperative implant insertion was simulated using an implant-bone interference fit of 50 microns and friction coefficient of 0.4.[20,21] Single-leg stance in a 70 kg person was simulated with a static load of 3 kN applied at a 20° angle to the implant, and abductor muscle load of 1.25 kN applied at a 20° angle to the greater trochanteric insertion.[22] Twisting with a planted foot was simulated by applying a torque of 7 Nm to the implant.[23] Interference fit and friction coefficient were maintained in all simulations. The distal femur was fixed in all simulations. Loading scenarios were performed for all five implant designs. The magnitude and location of maximum principal strain along the bone-implant interface was recorded, which has been demonstrated to most reliably predict femur fracture.[24]

Material properties of the femur (cortical and cancellous bone) and femoral stems (titanium and cobalt-chrome alloys) were obtained from the literature and incorporated into our analyses (Table 1).[25]

Results

Femoral strain during simulated implant insertion, single-leg stance, and twisting with a planted foot was highest with the short single wedge stem design (0.3850) and lowest with the standard-length single-wedge design (0.0520). Strain with the short single-wedge design was approximately 7-fold higher than that observed with the standard-length single-wedge design across all simulations. Femoral strain was similar with modular, double-wedge metaphyseal filling, and cylindrical fully coated stem designs. Strain with these 3 designs was approximately 3-fold higher than with the standard-length single wedge design (Table 2).

The location of maximum femoral strain varied by stem design, but did not vary with implant insertion, single-leg stance, or twisting with a planted foot. Maximum strain was at the lateral aspect of the proximal femur with the short single wedge, double wedge metaphyseal filling, and cylindrical fully coated designs. With standard-length single-wedge and modular designs, maximum strain was at the proximomedial femur. Strain was highest per unit surface area with the cylindrical fully-coated stem (Figure 4).

Within each stem design, strain was similar in magnitude across simulated implant insertion, single-leg stance, and twisting with a planted foot.

Table 1. Material properties for femoral bone and stems utilised in FE model.

Material	Young's modulus (E) (MPa)	Poisson's ratio (μ)
Cortical bone	17300	0.29
Cancellous bone	1000	0.29
Titanium alloy (Stem designs: short single wedge, standard-length single wedge, modular, double wedge metaphyseal filling)	113800	0.34
Cobalt-chrome alloy (Stem design: cylindrical fully-coated)	200000	0.30

Table 2. Femoral strain with primary THA stems during implant insertion, single-leg stance, and twisting with a planted foot.

Strain			
Stem design	Implant insertion	Single-leg stance	Twisting with planted foot
Short single-wedge	0.3797	0.3850	0.3772
Standard-length single-wedge	0.0520	0.0575	0.0523
Modular	0.1427	0.1456	0.1712
Double-wedge metaphyseal filling	0.1347	0.1520	0.1354
Cylindrical fully-coated	0.1341	0.1669	0.1340

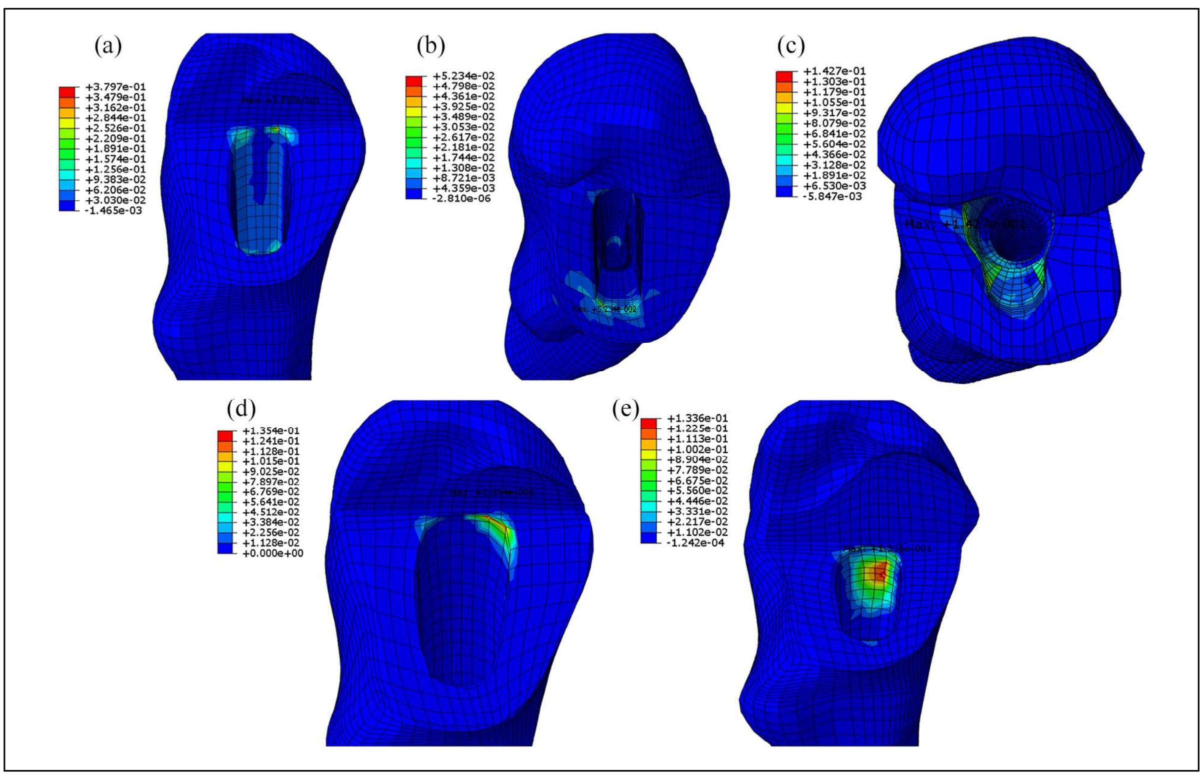

Figure 4. Representative geographic distribution and magnitude of femoral strain are demonstrated with (a) Short single-wedge (b) Standard-length single wedge (c) Modular (d) Double-wedge metaphyseal filling (e) Cylindrical fully-coated stems.
(Areas of increased strain in greyscale images are depicted in lighter shades of grey.)

Discussion

The number of revision THAs may be decreased by identifying THA stem designs that transmit force to the femur in a manner that minimises the likelihood of periprosthetic fracture.[8–10] Our study aim was to use FEA to identify which of the commonly utilised primary THA cementless stem designs is associated with the lowest risk of intraoperative and postoperative periprosthetic femur fracture.

Our results suggest the risk of intraoperative and postoperative periprosthetic femur fracture with THA in a Dorr A femurs may be highest with short single-wedge THA femoral stems; lower with double-wedge metaphyseal filling, modular, and cylindrical fully-coated stem designs; and, lowest with the standard-length single-wedge design. We found the location of maximum femoral strain during implant insertion varies with stem design. Femoral strain during intraoperative stem insertion, regardless of design, was surprisingly high as it was similar to that observed with single-leg stance or twisting with a planted foot.

In cadaveric and composite femurs, a short stem was shown to have a lower load to fracture than a standard-length stem.[26] Multiple recent clinical studies have recapitulated this finding and found a higher risk of periprosthetic femur fracture with a short single-wedge stem compared to its standard-length option in direct anterior approach THA.[27,28] Based on this work and our findings, consideration may be given to minimising the use of short single-wedge stems in THA. To minimise unrecognised intraoperative femur fracture, the lateral femoral neck cut and greater trochanter should be carefully scrutinised for cracks following insertion of short single-wedge, double-wedge metaphyseal filling, or cylindrical fully-coated stems. The medial femoral neck cut should similarly be evaluated intraoperatively after insertion of standard-length single-wedge and modular stems.

Though our study may provide information helpful in the selection of a femoral stem for utilisation in THA, we understand our work has limitations. First, since we did not use clinical data, we may not have studied all scenarios that place patients at risk for postoperative periprosthetic fracture. However, by using FEA to compare stem designs, we were able to eliminate the effect of confounding factors such as variation in bone quality, intraoperative surgical technique, postoperative rehabilitation protocols, and patient behaviour. Second, the interaction between bone geometry and stem design was not examined since only a single Dorr A femur was modeled in our analysis. Gromov et al.[29] reported an increased risk of periprosthetic fracture when a double-wedge metaphyseal filling stem is utilised in a Dorr Type C femur. As a result, our findings may not be generalisable to patients of all bone geometries undergoing THA. Third, the stem designs studied were all of a single manufacturer, so the effect of subtle differences in geometry within a given stem design between manufacturers is unknown. In a study of the Nordic Arthroplasty Registry, Thien et al.[30] observed a difference in risk of revision for early periprosthetic fracture among double wedge metaphyseal filling stems from a variety of manufacturers.

Our results suggest the risk of intraoperative and postoperative periprosthetic fracture with THA in a Dorr A femur is highest with short single-wedge stems and lowest with standard-length single wedge stems. Maximum femoral strain is as high during intraoperative stem insertion as it is during weight-bearing activities and varies in location by stem design. Future work will include FEA with models of femurs from patients of diverse age, gender, race, and geometry to confirm the generalisability of our findings. Comparison between cementless and cemented stem designs will also be performed.

Declaration of conflicting interests

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