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Original Research

Biomechanical Behavior of an Hydroxyapatite-Coated Traditional Hip Stem and a Short One of Similar Design: Comparative Study Using Finite Element Analysis

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ABSTRACT

Background: The objective is to compare, by the means of finite elements analysis, the biomechanical behavior of a conventional stem of proven performance with a short stem based on the same fixation principles.
Methods: A 3D femur was modeled from CT scan data, and real bone density measures were incorporated into it. Load stresses were applied to that bone in 3 different scenarios: without prosthesis, with the conventional stem, and with the short stem. Different bone loading patterns were compared by Gruen's zones both visually and statistically using Welch's test.
Results: The implantation of a stem generates a certain degree of stress shielding in the surrounding bone, but the pattern of the change is very similar in the compared stem models. Although there is statistical significance ($P < 0.01$) in the mean stress variation in most of the Gruen's zones, the magnitude of the difference is always under 2 MPa (range: 0.01 − 1.74 MPa).
Conclusions: The bone loading patterns of the traditional stem and the short stem are very similar. Although there is no evidence of a link between biomechanics and clinical outcomes, our results may suggest that theoretical advantages of short stems can be exploited without the fear of altering bone loading patterns.

Introduction

Although the results of total hip arthroplasty are excellent, with mean survival rates of over 92% at 14 years [1], some aspects of the clinical performance of conventional stems could be improved, such as the rate of early periprosthetic fractures [2,3], thigh pain [3-6], proximal stress-shielding [3,6-9], and loss of bone stock for possible future revision [3,6]. These issues have led to the appearance on the market of a wide variety of stems aiming to reduce bone mass loss, achieve a more physiological load distribution, and facilitate less aggressive surgical approaches [9-12]. These stems are generically called short stems; however, this term represents a very heterogeneous group with different designs, biomechanics, and invasiveness [9,10,13,14].

Short stems are not without problems. Certain designs preserving the femoral neck require a more complex technique [12,14-16] and are less tolerant of placement errors, size selection, or level of

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bone resection [10]. In addition, a high frequency of poor alignment has been associated with some models [7]. As a result, many surgeons only use short stems in young patients with good bone quality [10,14,17,18].

Studies using the finite element method provide information on biomechanical behavior, in particular regarding micromotion and load transfer [19,20]. This method has also been used to study the effect of the collar, present in some prosthetic designs, on the biomechanical behavior of the femoral implant [21].

The aim of this study is to compare, using finite element method, the biomechanical behavior of a conventional stem of proven performance [1,15,22-24] with a short stem design seeking to reduce bone mass loss in the trochanter and diaphysis but maintaining the same fixation principles.

Materials and methods

A frozen femur from a 46-year-old male individual without antecedents of interest was used to model the system under study. A computerized axial tomography scan of the femur was performed to obtain the bone density of the specimen in Hounsfield units [25-27]. The data were incorporated into a voxel model (cubic units making up a three-dimensional object) using modVOX software (MBA, Inc. Gijón, Spain). Voxel models allowed assigning the mechanical properties of the different points of the original bone directly to each individual model voxel, having a spatial position (x, y, z) to which the bone density obtained from the base tomography was assigned.

The stems to be compared were also modeled, including information regarding their composition. The following implants were used (Fig. 1):

- Furlong H-A.C. (JRI Orthopedics Ltd., Sheffield, United Kingdom): hydroxyapatite-coated titanium stem, 152 mm long, fitted with a collar. Its primary fixation is based on a quadrangular metaphysis and a long stem, joined by a tapered transition zone;
- Furlong Evolution, collarless version (JRI Orthopedics Ltd., Sheffield, United Kingdom): hydroxyapatite-coated titanium, 100 mm long; it has a laterally reduced metaphysis, and its medial curve presents a bigger radius. While it maintains the tapered transition zone, stem is merely testimonial; and
- Furlong Evolution, version with a collar (JRI Orthopedics Ltd., Sheffield, United Kingdom): Identical to the previous one, but with a collar.

Both short stems have been designed to preserve maximum bone mass and can be inserted with a simpler surgical technique, without the need to prepare the antirotation tab in the trochanter.

Digital bone preparation and implant positioning were performed according to the standard surgical technique, as agreed by all the authors. Two types of models were obtained: One was a femur model before stem placement, and the second was a femur model with each of the 3 stems used. These voxel models were exported to exchange files that could be interpreted by Ansys software (Ansys Inc., Canonsburg, PA) to determine internal bone stresses between bone and stem.

In the finite element analyses, the boundary conditions defined by Bergmann et al [28], which include the forces exerted by the joint and abductor muscles, were considered in the models. Bone fixation was performed on the outer nodes of the distal femur, from the condyles to a dimension of 150 mm [29].

The analysis results provided information on bone stress in the nonoperated femur and in those with the different types of stems implanted. As these data were assigned to elements with a defined spatial location (x, y, z), it was possible to compare the stress change produced in each bone element before and after implantation of each prosthetic model.

A qualitative and a quantitative method has been chosen to interpret the results.

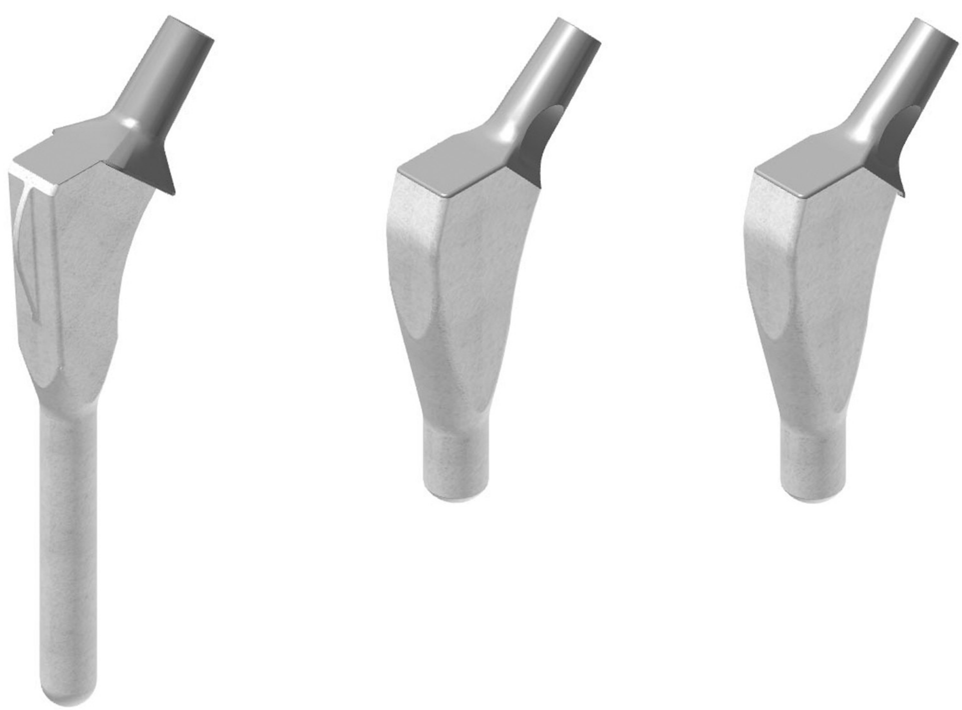

Figure 1. The 3 stems compared in the study: Furlong H-A.C., collarless Furlong Evolution, and collared Furlong Evolution.

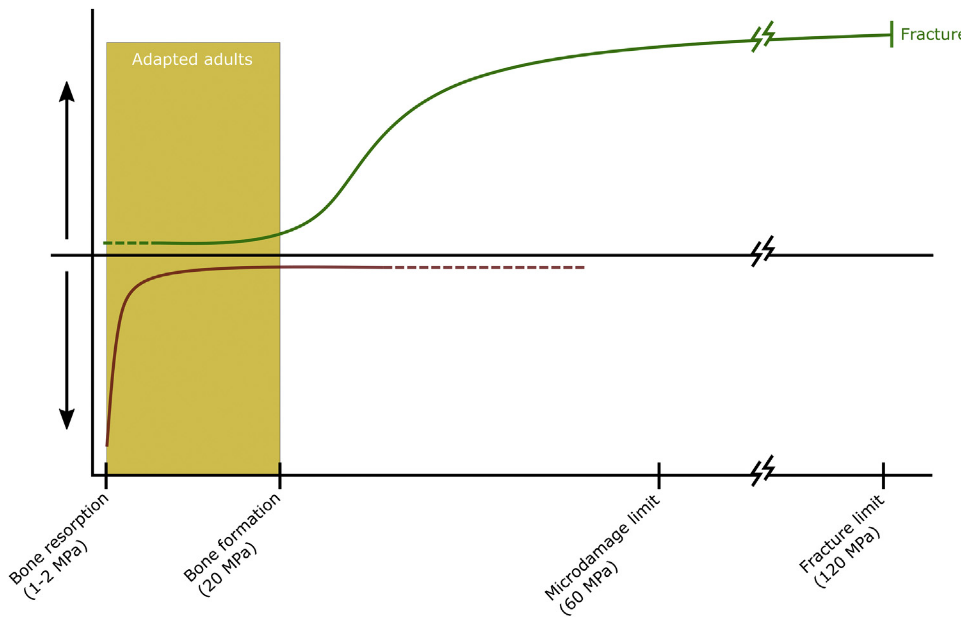

Figure 2. Bone behavior under stress according to the Utah paradigm and the mechanostat hypothesis.

Qualitatively, visual analysis of a graphic representation of the stress variations observed in the bone when implanting each type of stem was used to evaluate the implication of the findings. VTO3D software generates a voxel for each comparable node, assigning it to a layer with a certain color depending on the stress deviation. The changes were studied based on the Gruen zones in the anteroposterior and lateral views (zones 1-14) [30].

Quantitatively, the voxels were segmented according to the Gruen zones in the anteroposterior view [31], and the mean stress change in each of those zones was calculated for each type of stem. For comparative reasons, the zones originally described by Gruen were used for both the conventional and short stems. The method described by Roces-García et al [32] was used to analyze the similarities and differences between the biomechanical behavior of the conventional and short stems.

Because the stress changes (increase, decrease, or invariable) are different for each element, these were grouped into ranges or categories to simplify the analysis. To determine reasonable ranges of stress variation, we relied on the Utah paradigm and mechanostat hypothesis [33], according to which mechanical stimuli are the essential factors for their determination. The forces acting on the bone cause small strains, which result in an adaptive response by the bone. Frost [33] described bone modeling thresholds based on the amount of microstrain suffered with respect to the total length: Bone resorption occurs below 1 or 2 MPa (50-100 $\mu\varepsilon$), net bone formation occurs above 20 MPa (1000 $\mu\varepsilon$), and the remodeling rate is stable between these values, with neither bone formation nor resorption [33] (Fig. 2).

For the present analysis, it was assumed that individuals undergoing hip replacement surgery are normally distributed within the stress range of the adapted window in so-called adapted adults, with their bones in a state of relative stability and bearing physiological loads between 2 and 20 MPa [33]. It has been assumed that the level of stress change that would ensure any individual moving from relative stability to a local state of bone formation or resorption would be greater than ±20 MPa. Changes between 5 and 20 MPa with respect to baseline conditions have been considered minor and are represented graphically as such.

The analysis of stress variations was divided into 4 differentiated groups according to Table 1.

Importing these models into a computer-aided design environment made it possible to control the visualization, colors, and transparency levels in the Gruen zones. The changes induced in the bone environment by each stem model were studied, predicting their effects on bone according to the mechanostat hypothesis [33]. Similarly, bone remodeling patterns were analyzed for each type of implant to perform a comparative analysis between them.

For the statistical analysis, a difference in means test was performed between the different stems and for each Gruen zone. Levene's test was performed to compare the variance between the different comparison groups, verifying the nonexistence of homoscedasticity. Group comparisons were performed with Welch's test,

Table 1
Tensional variations with respect to nonprosthetized bone (color code).

Color	Description	Bone stress	Interpretation
(red)	Relevant stress increase	△ 20 MPa	Bone formation in most people.
(orange)	Mild stress increase	△ 5-15 MPa	Bone formation in people who are above average.
(green)	Mild stress reduction	▽ 5-15 MPa	Bone resorption in people who are below average.
(cyan)	Relevant stress reduction	▽ 20 MPa	Bone resorption in most people.

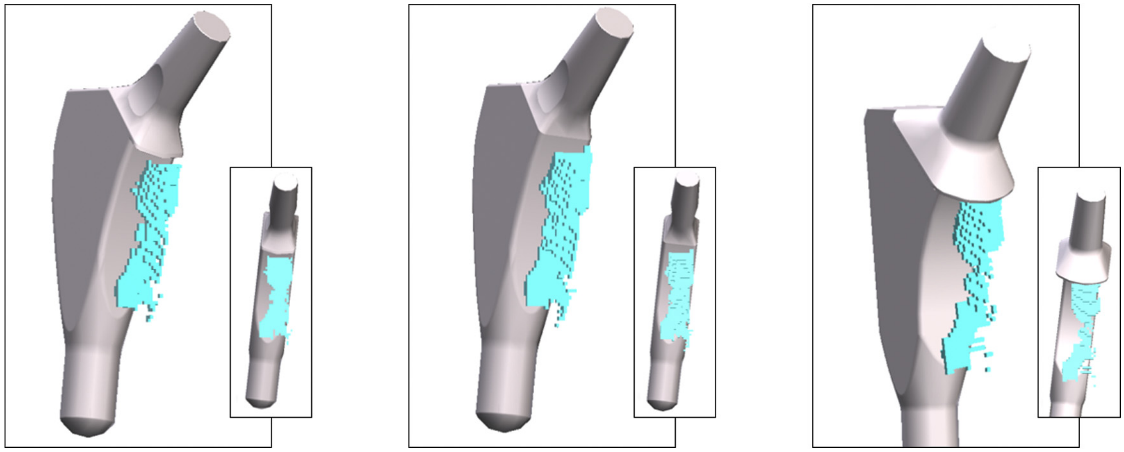

Figure 3. Relevant stress reduction area in the 3 compared stems (three quarters view). From left to right: Evolution (collared), Evolution, Furlong H-A.C.

and post hoc contrasts were based on the Games-Howell test. All calculations were performed with SPSS v.24 (IBM, New York, NY).

Results

Qualitative analysis

Gruen zones are shown in the anteroposterior and lateral views [30].

Stress decreases above 20 MPa

The 3 stems generated stress decreases greater than 20 MPa in areas 7, 14, and 13. According to the criteria already described, this would involve some degree of bone resorption, depending on the effects of the previous state of each individual. This decrease in the loads borne by the bone is more pronounced in short stems (Figs. 3 and 4). In addition, a slight difference in the loading pattern is detected in the conventional stem, offering less protection against stress in the central zone of that area (Fig. 3).

The data in Table 2 show the stress decrease extends over a larger area in the case of short stems (more voxels with a stress decrease). It is also observed that for the conventional stem, protection against stress is more visible in area 7 below the collar (Fig. 4).

The collar does not seem to have an important effect on load transfer to the bone, as there are hardly any differences between the loading patterns of the 2 short stems (with and without a collar).

Stress increases above 20 MPa

There were no areas with stress increases above the relevant threshold in any of the stems considered.

Stress decreases between 5 and 20 MPa

The slight stress decrease follows a similar pattern in all models. It occurs in the anterior zone of the trochanteric massif (zones 1 and 8), as well as in areas 3 and 5. In all the stems, the moderate stress decrease extends distally with respect to the stem, thus affecting a larger area in the conventional stem (Table 2 and Fig. 5)

In the posterior femoral region, there is also a slight stress decrease along the implant (zones 12 and 13). This protection against stress also occurs in short stems, but given the shorter length, the affected area is much smaller (Table 2 and Fig. 5).

The anterior area of the diaphysis does not show stress changes in any of the implants, including the long stem.

A small difference between the conventional and short stems is a zone of slight stress decrease at the proximal edge of the osteotomy, in the posterior femoral region (Table 2 and Fig. 5).

Stress increases between 5 and 20 MPa

All stems generate an area of moderate stress increase in the medial and lateral aspects of the femoral shaft, zone 4 (Fig. 6). This area begins just below the distal end of the conventional stem and may seem related to this finding, but it is also present in short stems and appears at the same height (although its extension is somewhat greater in the conventional stem).

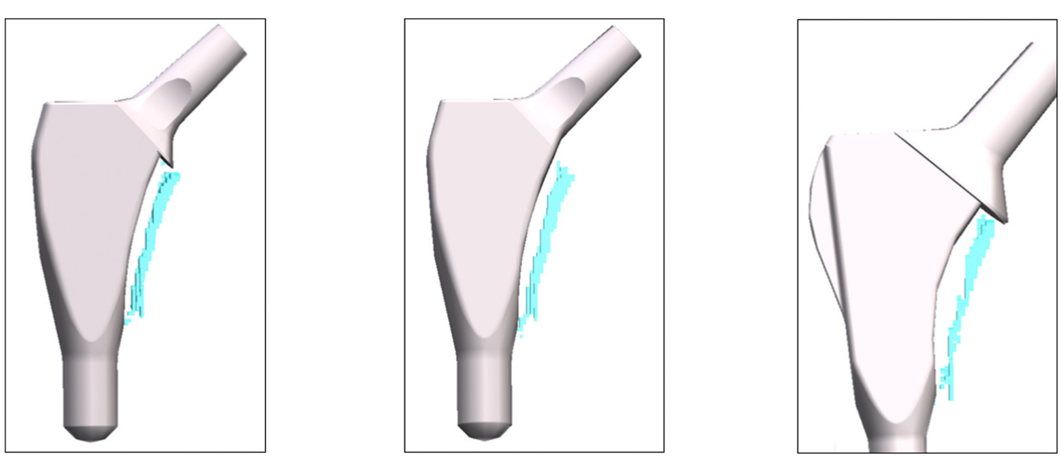

Figure 4. Relevant stress reduction area in the 3 compared stems (axial view). From left to right: Evolution (collared), Evolution, Furlong H-A.C.

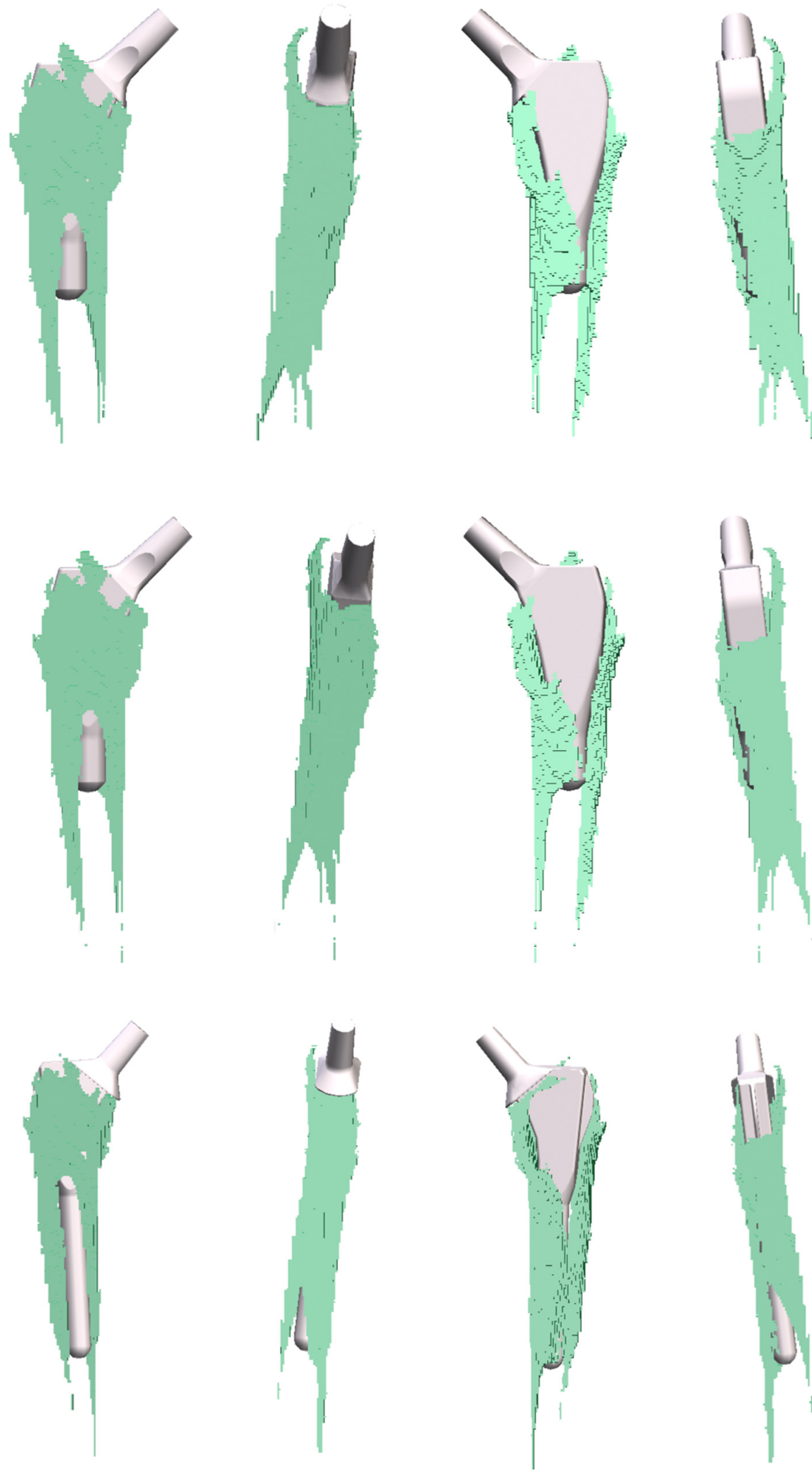

Figure 5. Mild stress reduction area in the 3 compared stems. From top to bottom: Evolution (collared), Evolution, Furlong H-A.C.

Table 2
Number of voxels according to the type of tensional change produced and segmented by area of Gruen.

Stem	Gruen zone	Number of voxels			
		Increase of tension	Reduction of tension	No tensional change	Total
Furlong H-A.C.	1	5454	42,107	60	47,621
	2	622	17,570	0	18,192
	3	2543	17,435	2	19,980
	4	29,127	12,762	20	41,909
	5	7872	12,896	3	20,771
	6	372	14,627	1	15,000
	7	14	26,014	0	26,028
Evolution	1	6299	37,759	67	44,125
	2	714	15,241	1	15,956
	3	11,401	13,528	21	24,950
	4	29,403	12,474	32	41,909
	5	9314	16,916	17	26,247
	6	350	15,644	0	15,994
	7	59	24,786	0	24,845
Evolution (with collar)	1	6253	37,789	61	44,103
	2	709	15,209	2	15,920
	3	10,976	13,955	19	24,950
	4	29,040	12,850	19	41,909
	5	8971	17,256	20	26,247
	6	343	15,701	0	16,044
	7	45	24,532	0	24,577

A very small area of stress increase also appears in all models at the superior-posterolateral portion of the prosthesis (zones 1 and 14). This occurs independently of the geometry of the implant, although the Evolution stems have a smaller shoulder to facilitate insertion, avoiding the area of the greater trochanter.

Quantitative analysis

After grouping the finite elements according to the Gruen zone to which they belong, the mean stress variation was calculated for each stem in each Gruen zone [31]. The 95% confidence interval was also calculated, and a difference in means test was performed. The results are shown in Table 3 and Figure 7.

Statistical analysis revealed significant differences in all zones for the 3 stems. However, these differences were very small because of the amount of data obtained and should not imply major changes regarding bone behavior according to accepted principles.

Stress changes close to 1 MPa or higher have been selected, shown in blue in Table 3 and Figure 8. To represent those zones where the changes are minor, we have indicated in yellow the areas where the changes do not reach statistical significance (which are also very close to 0 MPa).

The biggest changes occurred in Gruen zones 3, 6, and 7 when comparing the conventional and short stems. Short stems slightly reduce stresses below the prosthesis while keeping them somewhat stable in the metaphysis.

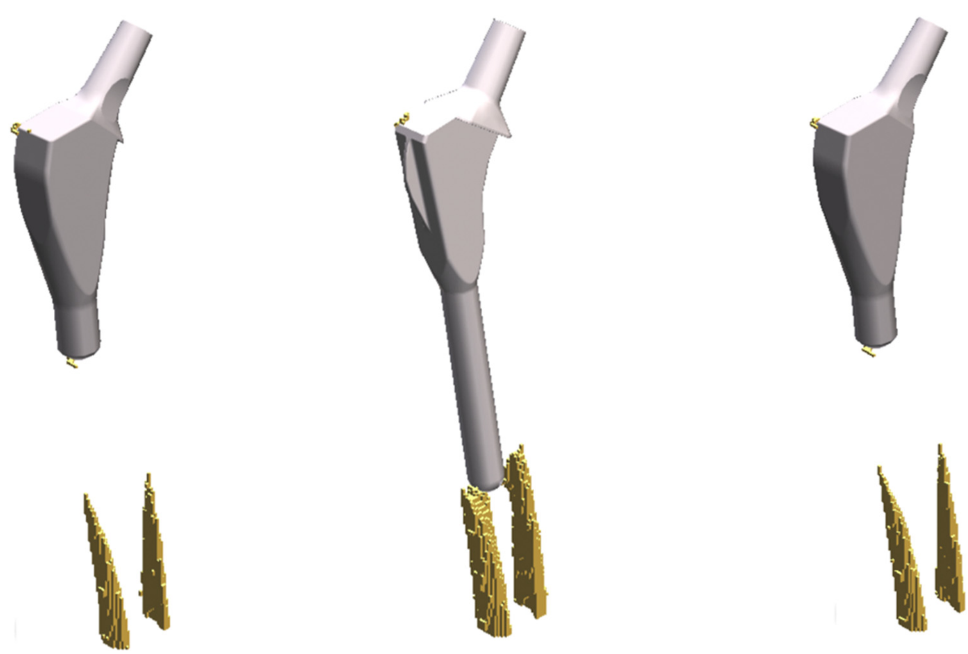

Figure 6. Mild stress increase was noted along the femoral shaft for all 3 stem designs. From left to right: Evolution (collared), Furlong H-A.C., Evolution.

Table 3
Mean tension differences between different stems by Gruen zones.

Gruen zone	Compared stems		Mean difference	Absolute value (mean difference)	Sig. (*P*)
	Stem A	Stem B			
1	Furlong H-A.C.	Evolution	0,10945	0,10945	0.000
		Evolution (collar)	0,10065	0,10065	0.000
	Evolution	Furlong H-A.C.	−0,10945	0,10945	0.000
		Evolution (collar)	−0,00880	0,00880	0.890
	Evolution (collar)	Furlong H-A.C.	−0,10065	0,10065	0.000
		Evolution	0,00880	0,00880	0.890
2	Furlong H-A.C.	Evolution	−0,17173	0,17173	0.000
		Evolution (collar)	−0,25919	0,25919	0.000
	Evolution	Furlong H-A.C.	0,17173	0,17173	0.000
		Evolution (collar)	−0,08745	0,08745	0.048
	Evolution (collar)	Furlong H-A.C.	0,25919	0,25919	0.000
		Evolution	0,08745	0,08745	0.048
3	Furlong H-A.C.	Evolution	−1,69292	1,69292	0.000
		Evolution (collar)	−1,67270	1,67270	0.000
	Evolution	Furlong H-A.C.	1,69292	1,69292	0.000
		Evolution (collar)	0,02021	0,02021	0.563
	Evolution (collar)	Furlong H-A.C.	1,67270	1,67270	0.000
		Evolution	−0,02021	0,02021	0.563
4	Furlong H-A.C.	Evolution	0,47471	0,47471	0.000
		Evolution (collar)	0,64009	0,64009	0.000
	Evolution	Furlong H-A.C.	−0,47471	0,47471	0.000
		Evolution (collar)	0,16538	0,16538	0.000
	Evolution (collar)	Furlong H-A.C.	−0,64009	0,64009	0.000
		Evolution	−0,16538	0,16538	0.000
5	Furlong H-A.C.	Evolution	0,49722	0,49722	0.000
		Evolution (collar)	0,33948	0,33948	0.000
	Evolution	Furlong H-A.C.	−0,49722	0,49722	0.000
		Evolution (collar)	−0,15774	0,15774	0.010
	Evolution (collar)	Furlong H-A.C.	−0,33948	0,33948	0.000
		Evolution	0,15774	0,15774	0.010
6	Furlong H-A.C.	Evolution	−0,99695	0,99695	0.000
		Evolution (collar)	−1,14925	1,14925	0.000
	Evolution	Furlong H-A.C.	0,99695	0,99695	0.000
		Evolution (collar)	−0,15230	0,15230	0.035
	Evolution (collar)	Furlong H-A.C.	1,14925	1,14925	0.000
		Evolution	0,15230	0,15230	0.035
7	Furlong H-A.C.	Evolution	−1,72197	1,72197	0.000
		Evolution (collar)	−1,73798	1,73798	0.000
	Evolution	Furlong H-A.C.	1,72197	1,72197	0.000
		Evolution (collar)	−0,01602	0,01602	0.695
	Evolution (collar)	Furlong H-A.C.	1,73798	1,73798	0.000
		Evolution	0,01602	0,01602	0.695

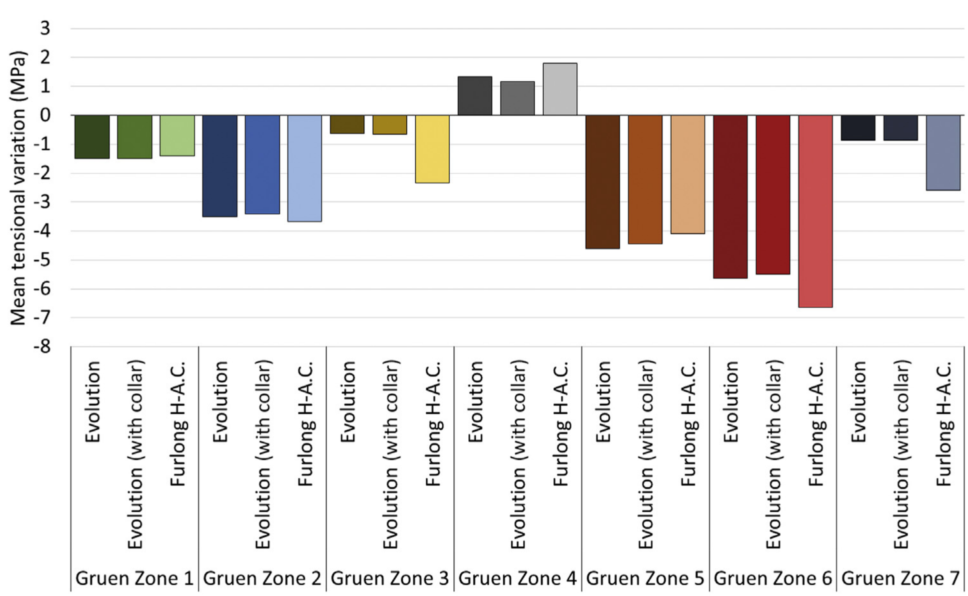

Figure 7. Mean tensional variation between the different stems by Gruen's zones.

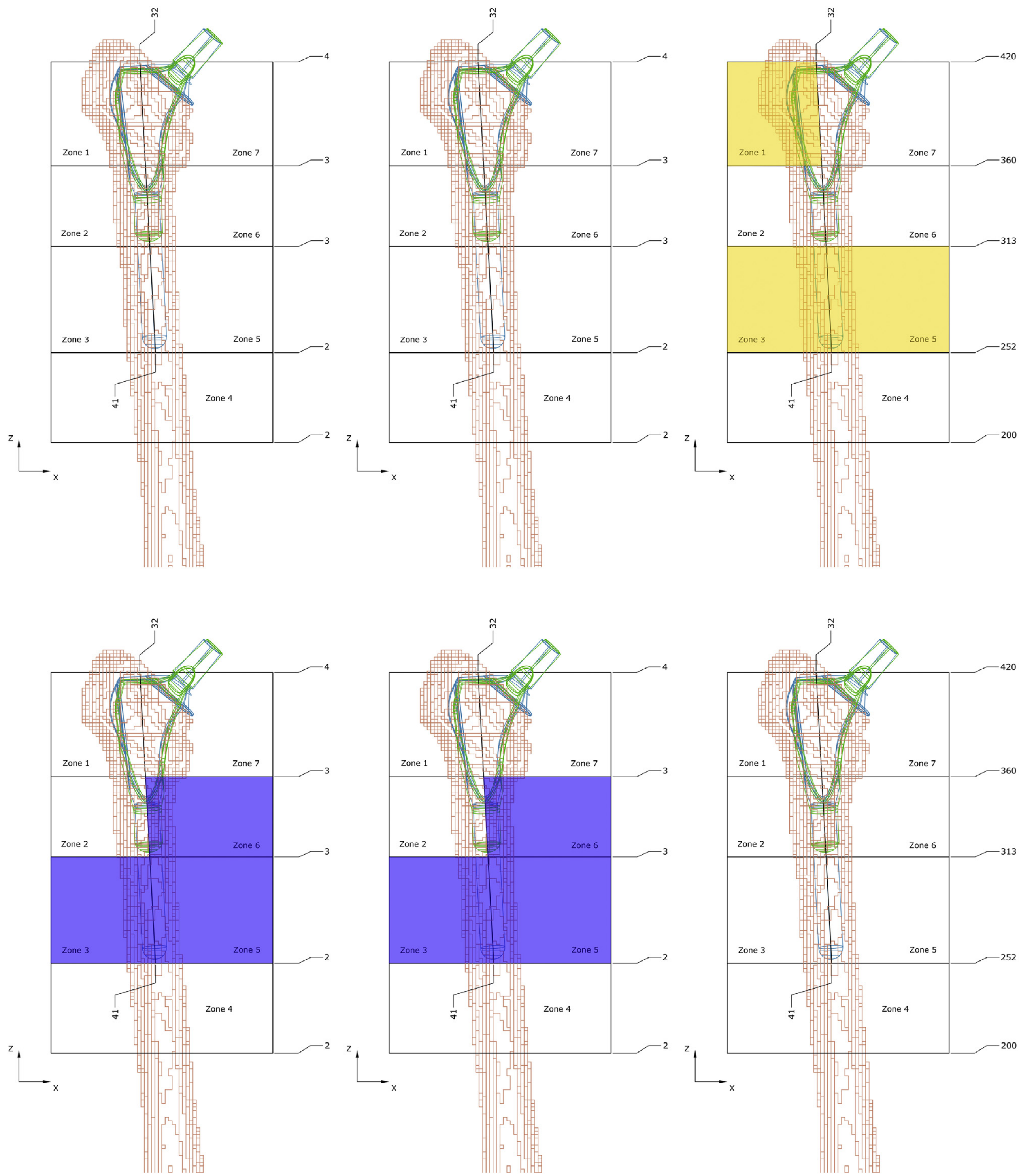

Figure 8. Gruen zones with and without statistical significance stress variation.

Discussion

From the biomechanical point of view, the ideal implant should replicate the physiological pattern of load transfer along the remaining bone after placement [6,34]. However, the implantation of any prosthetic model affects load transfer, usually causing proximal unloading of the stem and stress transfer to the distal region [34-38]. The typical outcome of this load transfer is metaphyseal bone resorption (with atrophy of the calcar and cortex of the proximal femur) and cortical hypertrophy at the distal end of the stem [34]. This is consistent with the observations in our models because the only clinically relevant stress decreases (above 20 MPa, as we have defined) occur in Gruen zone 7.

This study aims to analyze whether the biomechanical behavior of a "short" stem (Furlong Evolution with and without collar) differs from the previous design (Furlong H-A.C.). At the metaphysis (Gruen zones 1 and 7), the quantitative comparison of mean stress change between the stems analyzed, although statistically significant, is of a very low magnitude (0.11 MPa in zone 1 and 1.74 MPa in zone 7; Table 3); therefore, it would not have any clinical relevance [33]. This is consistent with the results found in other studies minimizing the clinical importance of the collar [21,39].

In Gruen zone 1 (greater trochanter), there are no significant stress changes. Although the short stem studied has a reduced lateral shoulder, the mean stress change in zone 1 is practically zero (0.11 MPa). Thus, this modification can be interpreted as positive because it does not alter the biomechanics of the area but facilitates implant insertion; it does not weaken the trochanteric bone and prevents preparing the antirotation tab present in the conventional stem.

At the femoral shaft, there are clear differences between the Furlong H-A.C. stem and Furlong Evolution short stem designs, where the stress pattern of short stems is much more similar to that of nonprosthetic bone. This also coincides with the results of previous studies, in which hip implants with shorter stems tend to induce less stress shielding and better replicate the physiological bone condition [40-43]. When changes in the physiological remodeling pattern are very large, higher rates of aseptic loosening and periprosthetic fractures would be expected, hindering revision surgery [34]. Therefore, short stems could be recommended from this point of view. The stress difference between conventional and short stems is greater (1.69 MPa) in the femoral shaft (Gruen zone 3), although not reaching physiologically relevant levels [33].

The visual and quantitative analyses performed show very similar patterns of bone stress changes for the 3 prosthetic models considered and are practically identical for the 2 short stem versions (with and without a collar). Although there is still no evidence that clinical results are related to changes in bone remodeling patterns [34], our study demonstrates the great similarities existing in the biomechanical behavior of conventional and short stems. Load distribution in the metaphysis is very similar, and although the differences are somewhat larger in the diaphysis, they are very small. In addition, stress behavior with the short stem more resembles that under physiological conditions; therefore, it could theoretically improve the clinical results of the implant.

We must bear in mind the present study has some limitations. First, there is no evidence linking bone remodeling to clinical outcomes [36]. Thus, we have proposed a comparison with a stem with proven clinical results, assuming a similar biomechanical behavior will have positive effects on patients. Second, an individual component is involved in bone remodeling that does not depend only on the implant [34,36,44]. Third, it should be mentioned that the tests have been performed on a single femur, assuming the population of subjects undergoing total hip arthroplasty is normally distributed across the range of stresses of the adapted window in adults, which may be an oversimplification.

Conclusions

Our study analyzes the influence of implanting femoral stems with different geometries, but similar fixation philosophies, on bone stresses of the femur. Although there is no evidence of a link between biomechanics and clinical outcomes [36], establishing the biomechanical similarity between 2 implants could imply similar long-term clinical behavior with the mentioned advantages of easier implantation. In conclusion, although there are significant differences in the stress changes produced by the 3 prosthetic models on the bone, these are so small that they probably have relatively little influence on the biology of the surrounding bone.

Conflict of interests

The authors declare there are no conflicts of interest.

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