Impact of Hip Arthroplasty Stiffness on the Biocompatibility

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Abstract

Background. Maintaining bone health after arthroplasty placement is of paramount importance. Different materials used in artificial joint manufacturing are available in the market. Some had remarkable success rates. Ceramics are a group of biomaterials that have to gain special attention as bearing surfaces. Many surgeons and biomechanics researchers attribute their successes to their tribologic features. These are indirect effects. *Methods.* We had used state of art tool, FEA and linear analysis, to explore another direct impact of these materials on bone remodelling. Strain energy density was used as an objective criterion to evaluate the better model. The Hip model was provided by the local hospital CT-scan database. The comparison was based on the distribution of the strain energy within the model. *Results.* Due to their high stiffness (high Young modulus) and their resistance to deformation (low poison ratio), they have a more important direct effect on the bone. Nevertheless, their implantation should be considered as part of the total stiffness. The pattern of the strain energy density is better when a judicious choice of ceramic is done. *Conclusions.* Biocompatibility is a design-dependent subject. Injodious material combination could result in poor performance of the arthroplasty which is reflected upon patient health and welfare. We concluded that in the careful application of ceramics survivability of the arthroplasty could be enhanced.

Keyword: Arthroplasty, Biocompatibility, Ceramics, FEA, Stiffness

Introduction

The hip joint plays a significant rule in the patient daily activity(1). This joint could need replacement in certain situations (2). Loading is an integral part of tissue maintenance(3). The

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loading had complex considerations that should be clear to understand the complication that results from any conditions that are deviated from that normal loading conditions (4)

Sound knowledge provides a sound basis to treat the diseased part and to explain morbidities associated with the current treatment to avoid them in the future

What is well known in orthopaedic surgery are

- Mechanical loads provide physiologic stimulation to the bone. Without such load, disuse atrophy will ensue (5)
- Stress shielding is resulting in more rigid hardware and stiffer assemblies (6)

These two rules could be a keystone in expanding our understanding of hard tissue replacements.

We aim to build a model that if give a result close to the reality it could be used to synthesize information regarding other models or anticipating what could happen with a supposed model(7). This could be denoted as a parametric approach(8). We had chosen the hip model as it has had features that demonstrate the concepts we try to reveal as well as it is one of the most replaced joints(9)

As biocompatibility is design-dependent, we want to explore the effect of different material combinations on the bone(10) so that we can draw a suggestion about the possible best configuration that could affect the patients` health and to compare numerically different arthroplasties models that are different from each other by the combination of the used materials.

Materials and methods

We used the COMSOL Multiphysics® software to perform the modelling (11)

The model was provided from the local hospital CT-scan database after anonymization of the data.

The material properties were provided from MATWEB which is a searchable online database of engineering materials(12), but we had done rounding of the modulus of elasticity of the material to make these values more perceptible

Material	Ɛ (GPa)	Poisson`s ratio	
PMMA	3	0.3	
Ceramic	300	0.22	
UHMWPE	1	0.46	
6Al4V	100	0.3	
Stellite	200	.03	
Cartilage	0.1	1.5	

Table 1

Mechanical properties of the used materials

- The alumina had a higher value than what we had supposed. This was calculated for zirconia-grade ceramic. So alumina even had greater stiffness
- The ageing of zirconia should be calculated with its thermal conductivity

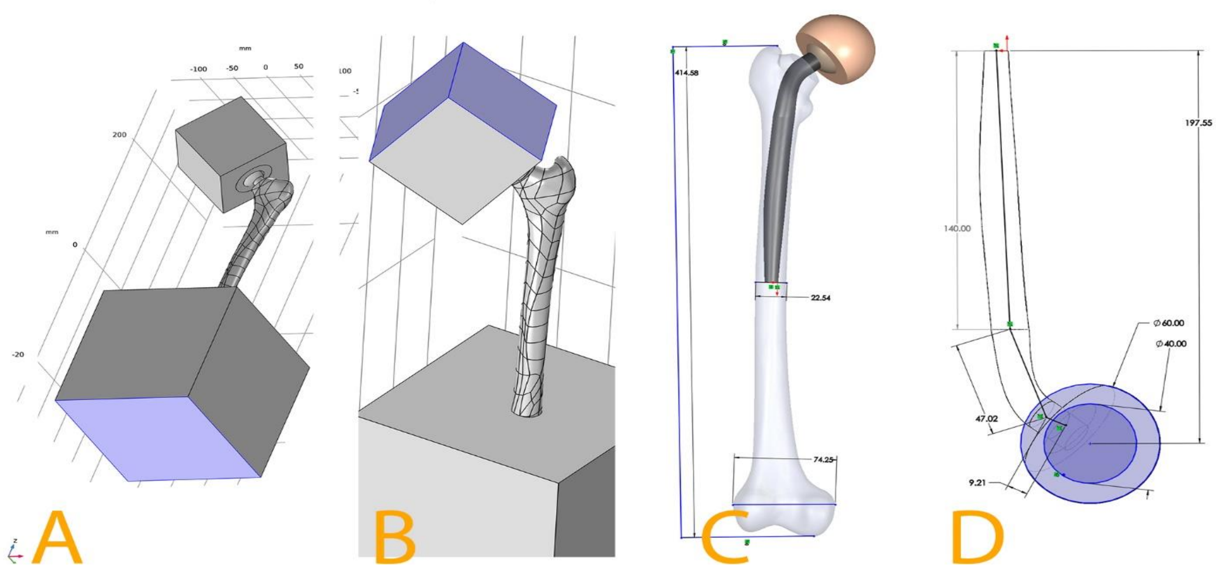

Figure 1

A The model was supposed to be well united and fixed from the base. B, the upper 2 surfaces of the holder had been displaced along the Z-axis by 1mm. C, the femur dimensions. D, dimensions of the arthroplasty.

The upper holder is a cube with 0.1m*0.1m*0.1m dimensions. The lower base had the double dimensions of the upper holder

The dimensions here were assumed theoretical, as our goal is to reveal the strain energy density pattern, rather than the seeking for the highest and lowest value. The finite models are mesh-dependent and we suppose them as soli monolithic in a linear fashion.

The mesh was generated to be fine with 35849 total elements and 7165 total vertices. The material supposed to be linear with an isotropic constitution and the loading condition was static.

The arthroplasty model was composed of the stem head and ace tabular component. Perfect osseointegration was assumed and the tolerances between ball and socket were zero with weld.

These conditions had been analyzed:

- The normal hip model with the presence of highly resilient material that is mimicking the cartilage layer between the femoral head and the acetabular bed
- Low to high gradient model where:

    - the acetabular component was assumed to be from UHMWPE
    - The ball was made from 6Al4V
    - The stem was made from ceramic
- High to low gradient model where:
    - the acetabular component was assumed to be from ceramic
    - The ball was made from 6Al4V
    - The stem was made from UHMWPE
- Intermediate gradient model where:
    - the acetabular component was assumed to be from ceramic
    - The ball was made from Stellite
    - The stem was made from 6Al4V
- The model where all the arthroplasty was made from UHMWPE
- The model where all the arthroplasty was made from 6Al4V
- The model where all the arthroplasty was made from Stellite
- COC model with 6Al4v stem
- MOM model with 6Al4v stem
- MOP model with 6Al4v stem

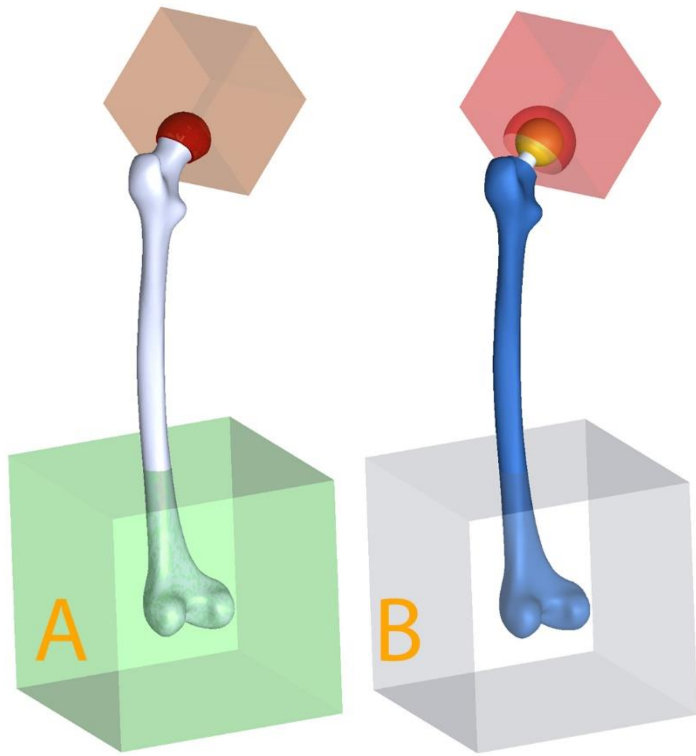

Figure 2

A normal hip model. B model with arthroplasty

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The strain energy criteria were post-processed to indicate the relevant bone response possible with our loading condition. Strain energy density had gain acceptance in the biomechanics community as a predictive tool for adaptive bone remodelling (13). Our evaluation was done for one aspect, which is the anterior aspect of the femoral bone. In all models, the legend was uniform to facilitate comparison and when we manipulate the colour-related value we had pointed for that.

Results and discussion

The results are clearly showing the distribution of the strain energy density. And as we are mostly want to reveal these regions the evaluation was qualitative and in the next papers, we could do a more statistical qualitative assessment.

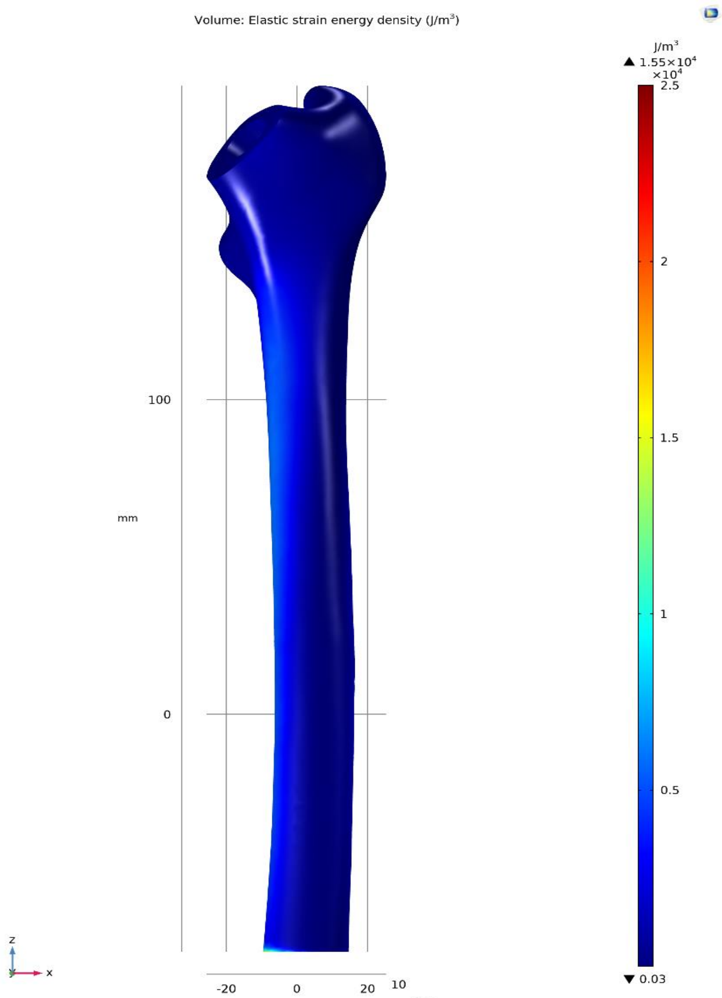

Figure 3

Bone model

Less strain energy density is concentrated closer to the femur head (more proximally)

All shafts are included in strain energy density. This distribution should be viewed in the context of bone micro architecture and macro architecture of the cortical and medullar bone regions. We know that bone overcorticalization will exceed the highest physiologic limit of the bone that leads to being one of the arthroplasties failure causes. (14, 15)

The bone transmits the stresses in the peripheral region, but in the case of arthroplasty, the stress will come from the core or inside. This will lead to a change of all architecture of the bone material that could lead to generalized disuse atrophy and osteolysis (16). This should be kept in mind that most of the patients who need arthroplasties are old age with more catabolism than anabolism(17)

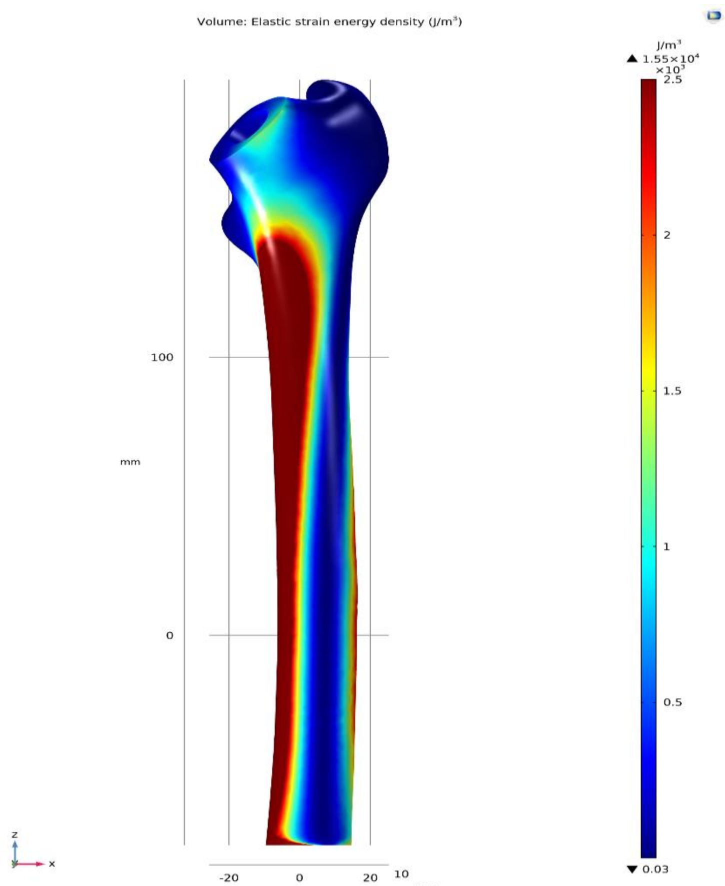

Figure 4

As the values of the strain energy are low in the case of the normal femur, in this figure we had manipulated the values to demonstrate the region with higher strain energy density

In the reality, the applied is always transient, so a higher stress application rate at the proximal part of the femur rendering the stresses shared by the more proximal part. For the distal part of the shaft, stresses will be less. In conjunction with the damping effect of the hip joint, the shaft will receive an even lesser amount of stress. While in the case of arthroplasty the shaft distal to the stem of the arthroplasty will receive unnatural highly concentrated stresses and strains. The shielding effect is even more pronounced in the proximal regions.

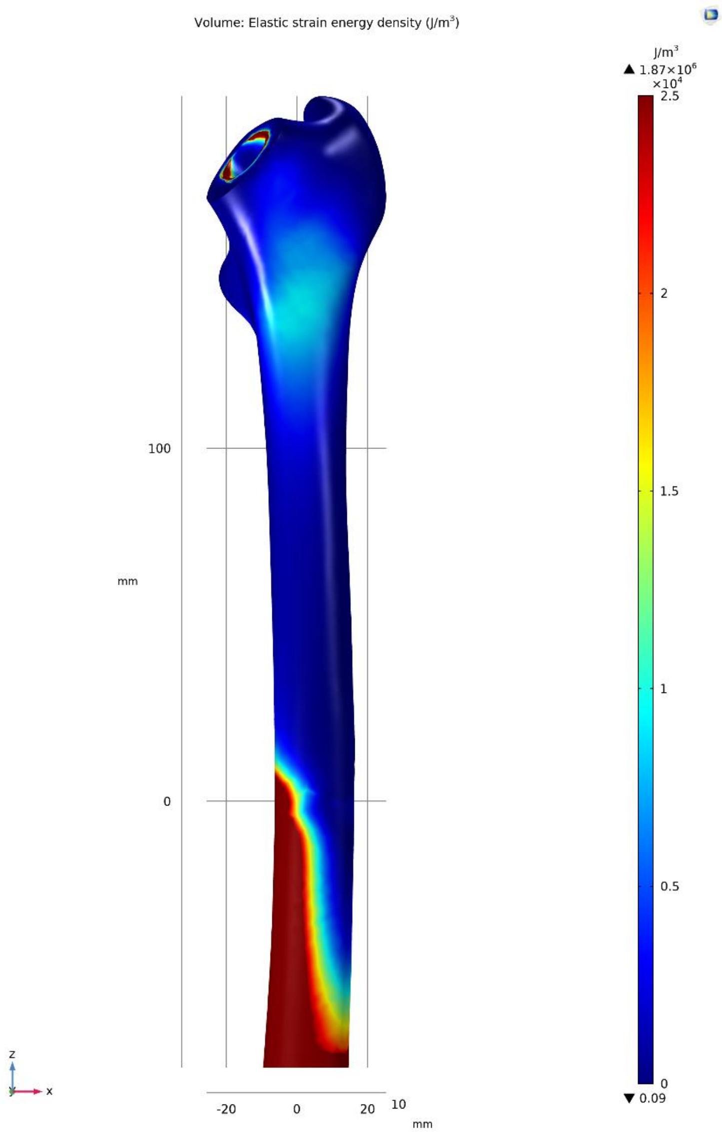

Figure 5

Low to high gradient model

This model had the poorest distribution in comparison to the other two gradient models. Gradients with the highest mechanical properties give closer results to the bone than other models. Although no such material is present nowadays(18), that provides such loading, one should keep developing current protocols and assemblies toward these results. The results of this model are inconsistency with clinical study (19) that indicate more bone loss is at the proximal part of the femur.

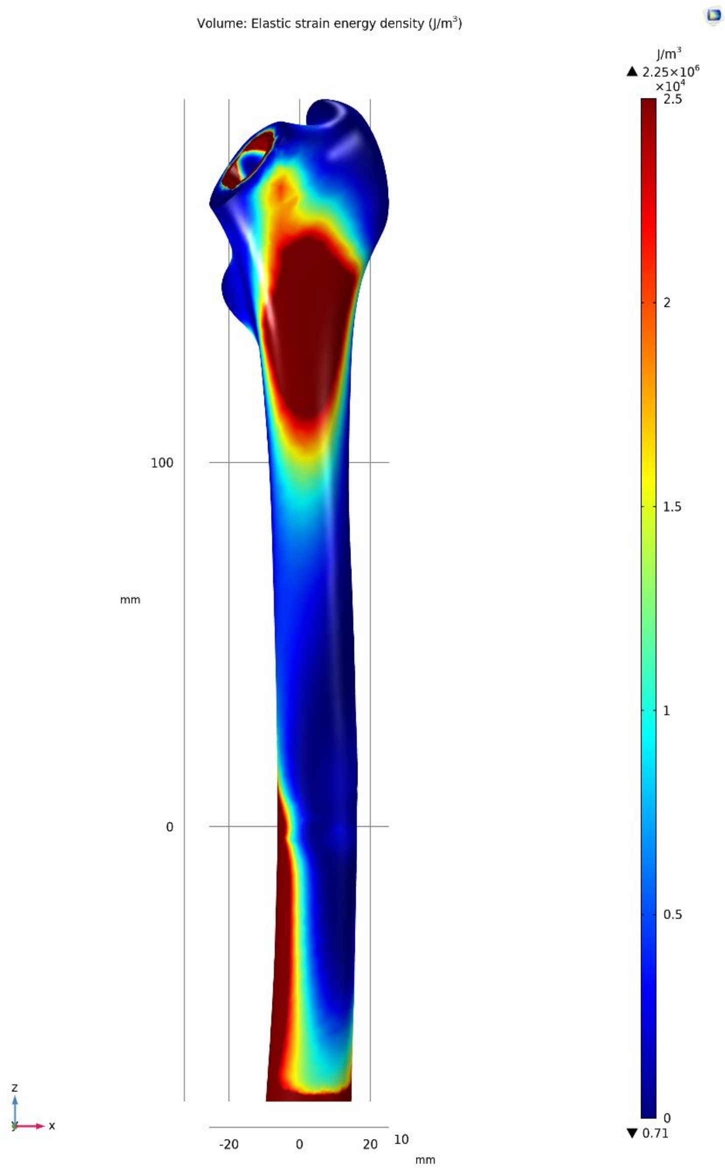

Figure 6

High to low gradient model

This model provides the best results among the other two gradient variants

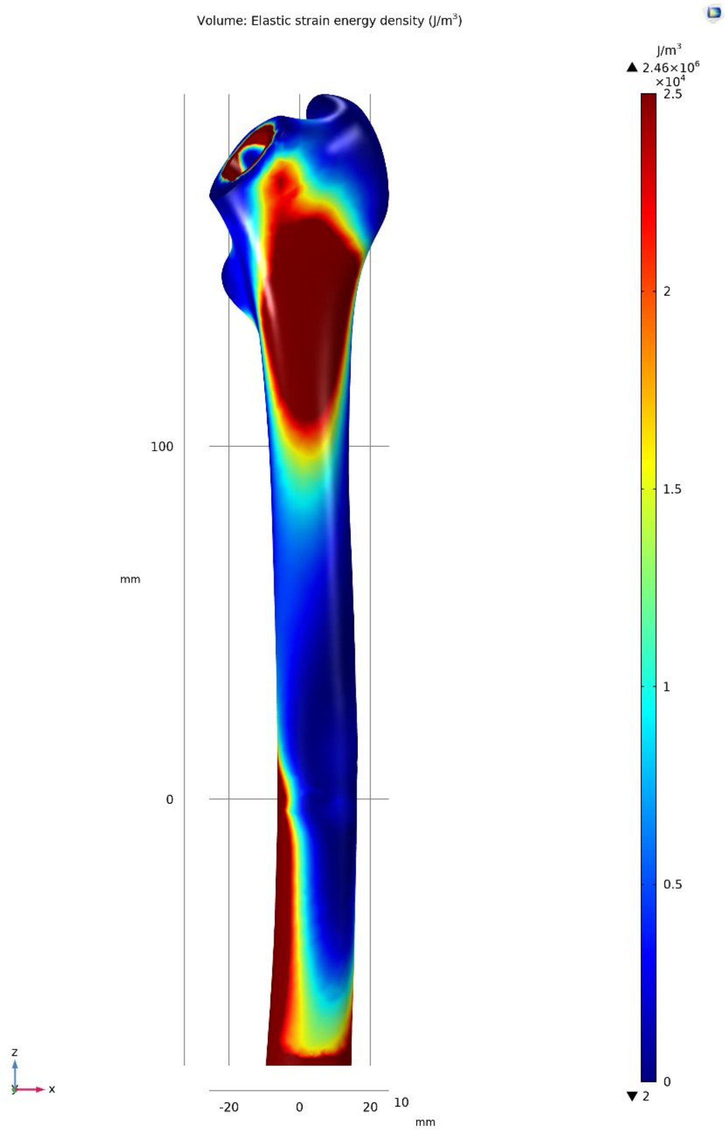

Figure 7

Intermediate gradient model

Surprisingly this model gives very close results to the low to high gradient model. This:

- should encourage us to choose stem of lower modulus of elasticity (20)
- using COC would even give more favourable results (21)

In both intermediate and high to low gradient models, higher energy in the proximal regions and less in the distal regions in comparison to the low to high gradient model due to stiffer stem.

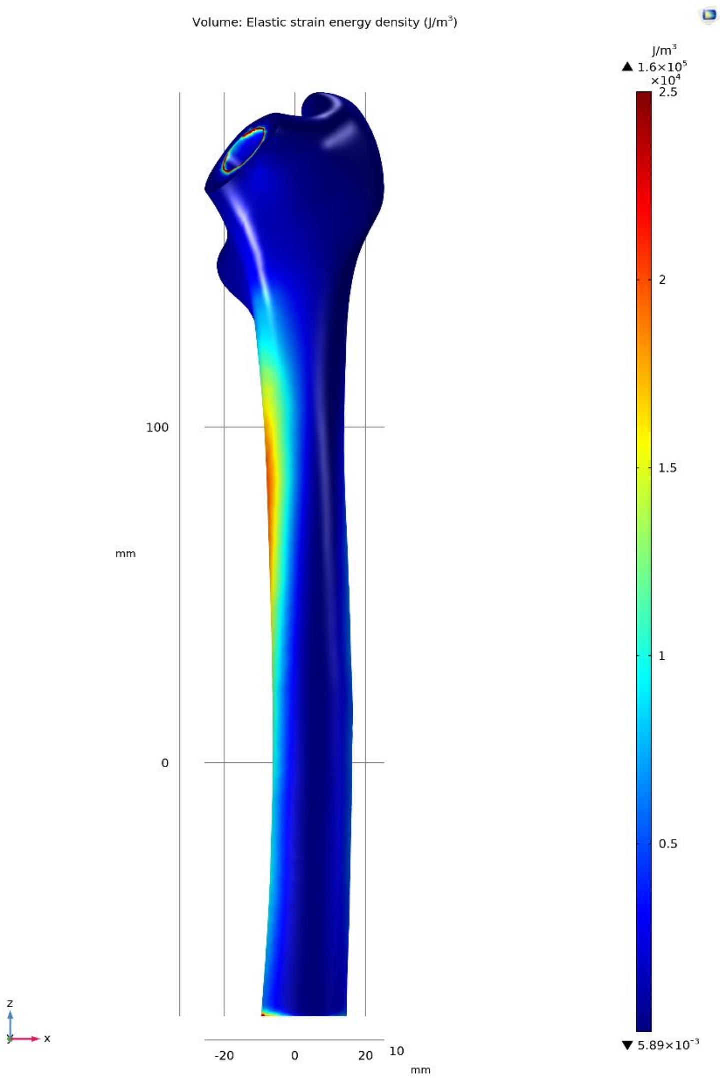

Figure 8

All polymer model

In all-polymer the capability of the stem to be bend demonstrated by the distribution of strain energy density on the shaft

Bone structure is not intended to receive stresses and strains from stiff material with such stiff connection (i.e. osseointegration), but it is designed to integrate with function with cartilage(22). In contrast to stiffer hardware, this region is more prone to more deformation.

The results of this model give the lowest possible highest value in comparison to other models, which could be easily explained if we know that the total energy is distributed more evenly providing excellent stimulation of the bone.

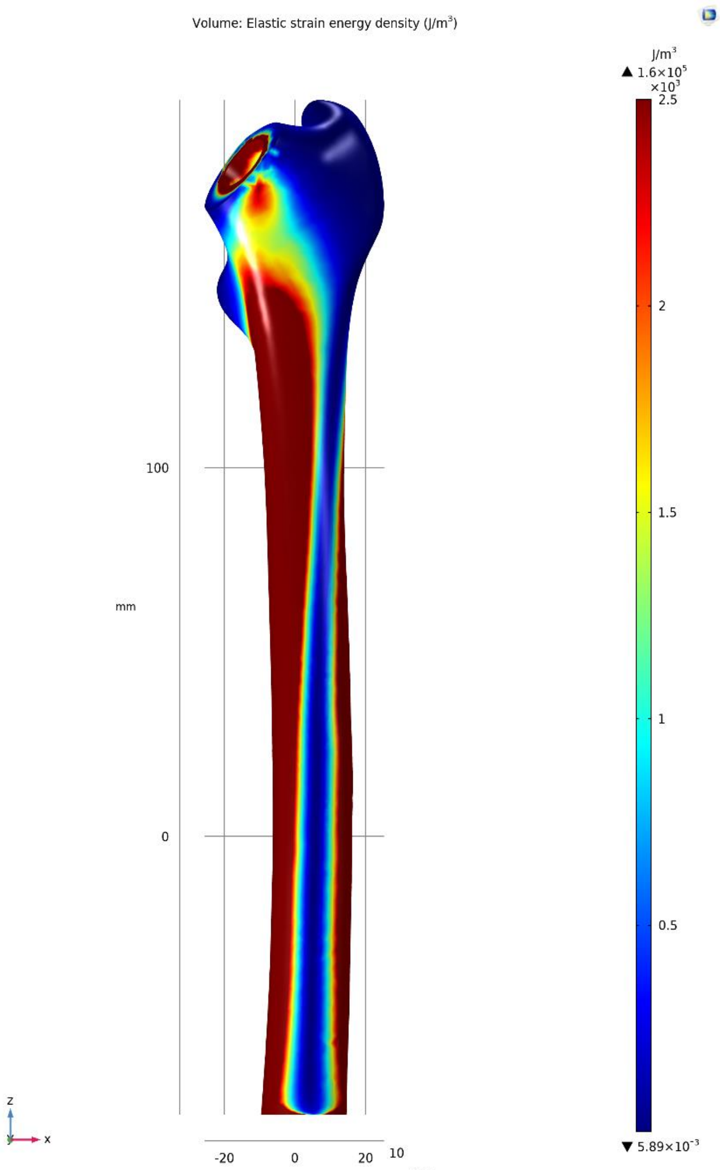

Figure 9

As the values of the strain energy are low in the case of the all-polymer model, in this figure we had manipulated the values to demonstrate the region with higher strain energy density. We had done this previously in the bone model

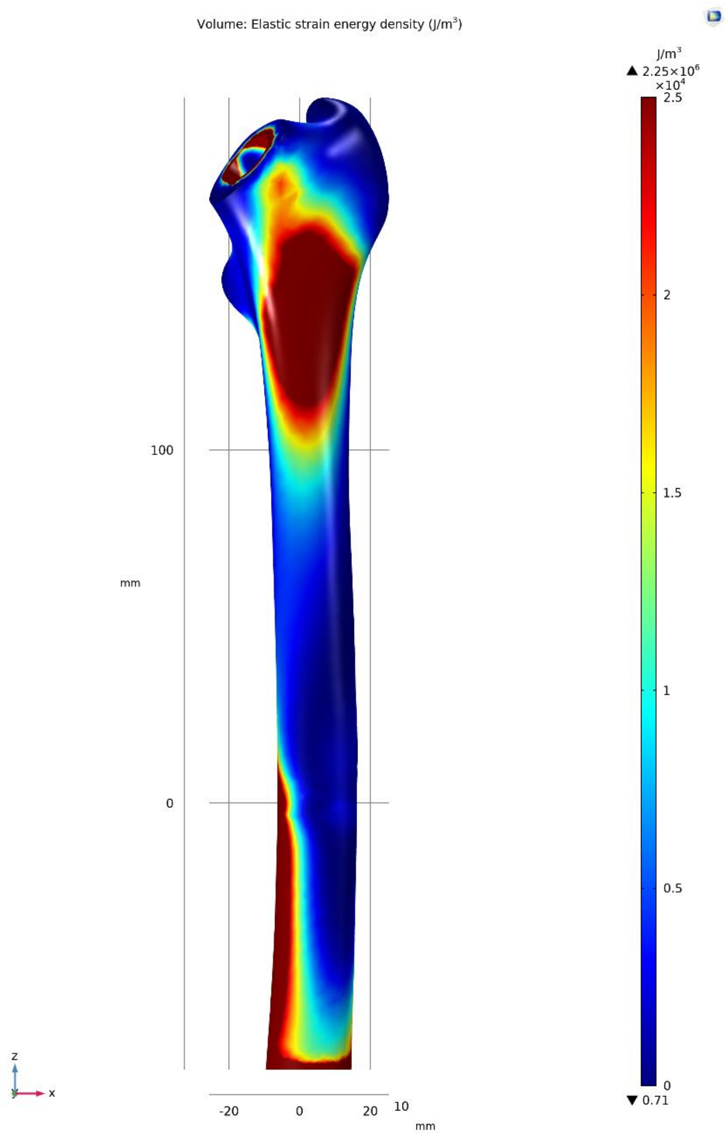

Figure 10

All 6Al4V model

In all metallic stem, the 2 region of strain energy density is present with an intermediate area devoid of this energy, but the more elongated area at the base close to the proximal region with higher values indicates the more healthy effect of this choice than Cr-Co-Mo alloy.

The dimensions of the stem should be revised carefully according to the net replacement stiffness(23, 24). Nevertheless, a longer stem could allow for earlier rehabilitation, but in the long term, it could lead to more devastating events.

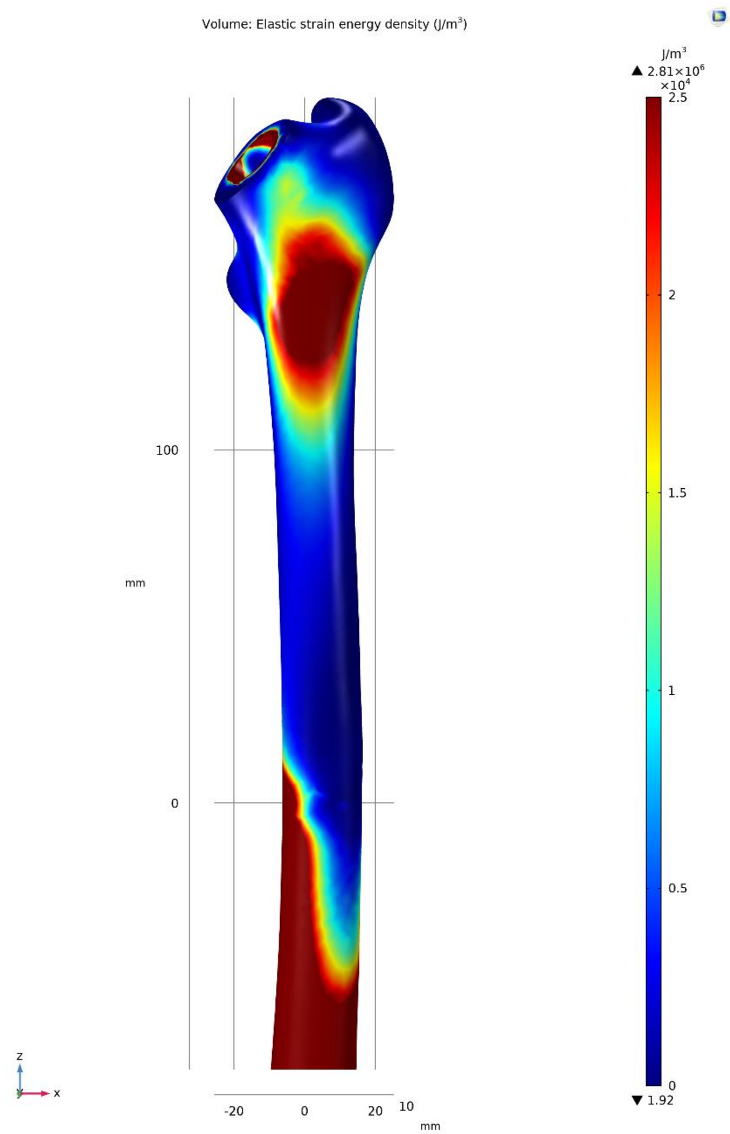

Figure 11

All Cr-Co-Mo alloy

The result with monolithic models gives a clear transition in the models according to the modulus of elasticity.

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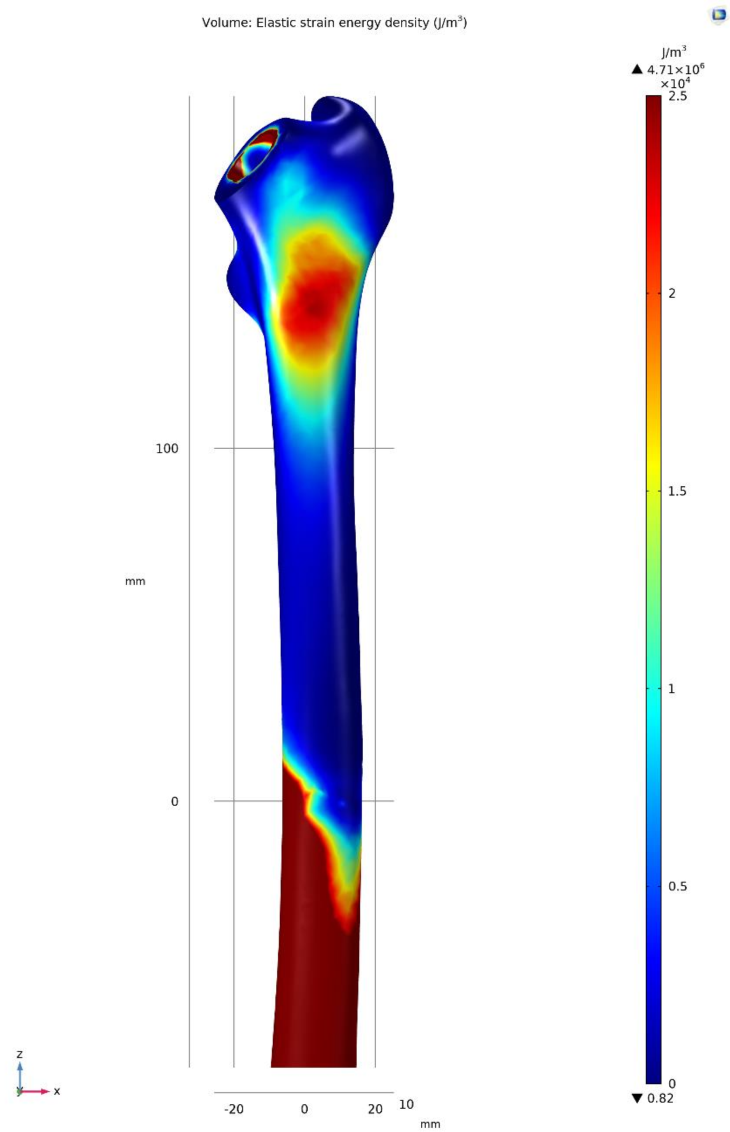

Figure 12

All ceramic model

The changing stress distribution toward the unfavourable condition is evident in this model. Comparing this and other models to all polymer models reveals the intermediate transitional zone in the femur shaft that made the vast majority of energy occur at the base as we suggest.

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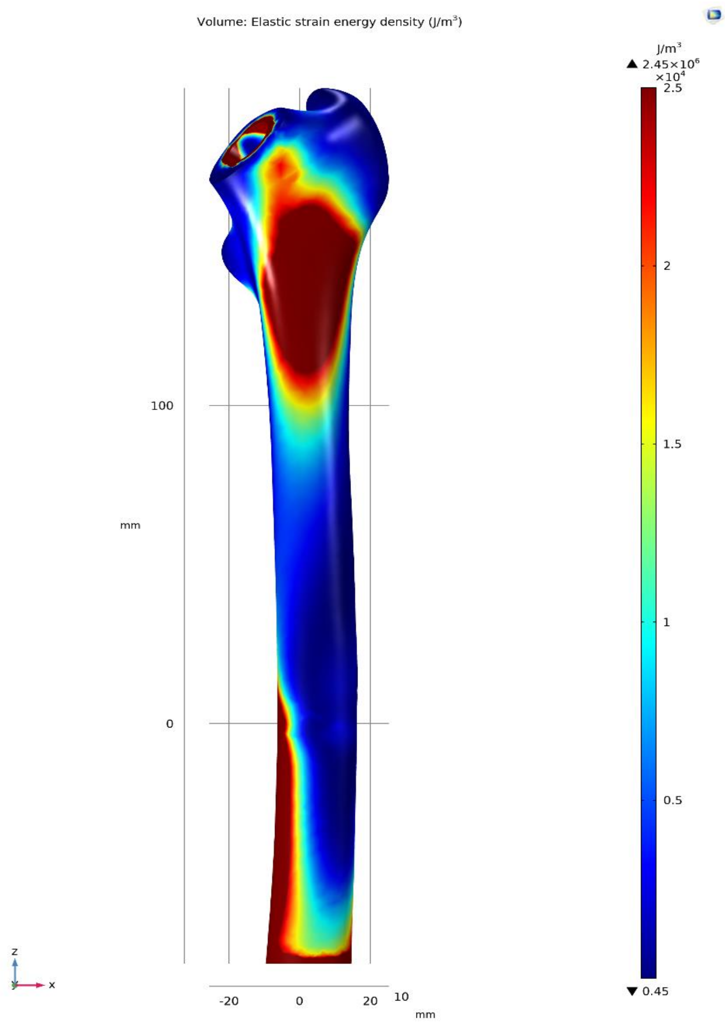

Figure 13

COC model

The effect of the material choice on bone physiology was revealed. The stiffer area at the bearing surfaces with the least stiff region of the assembly at the stem could result in more favourable physiologic stimulation and possibly better survival.

The lower region is almost identical in all models:

- MOP
- MOM
- COC
- All 6Al4V
- Intermediate gradient model

As all these models share the same stem material, even the highest value is close to each other and the only model that is significantly different is the MOP. We emphasize that this is one of the causes that give more favourable results when using COC-bearing couples. The stiffest material accompanies the higher ability to transmit the stress provides the best physiologic stimulation among these conditions. But the difference in the more proximal area is evident. This increased stimulation proximally resulted in a more healthy effect than in models with decreased energy at the same corresponding regions.

COC and the intermediate gradient model give very close highest resulted values. This is because the Stellite had a high modulus of elasticity closer to the ceramics than all of the other materials

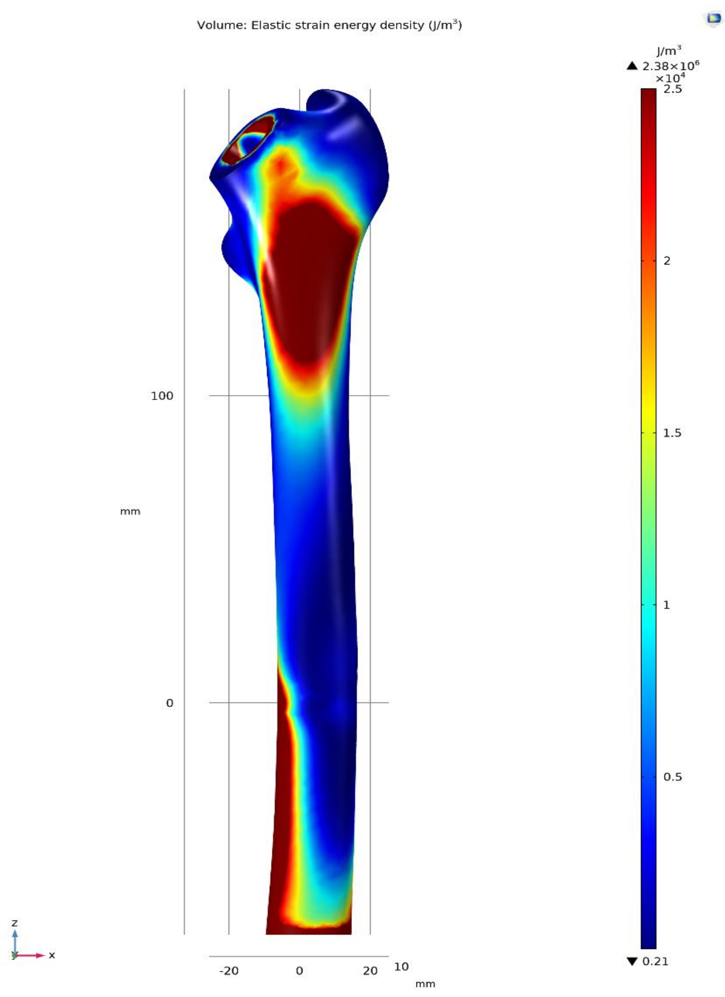

Figure 14

MOM model

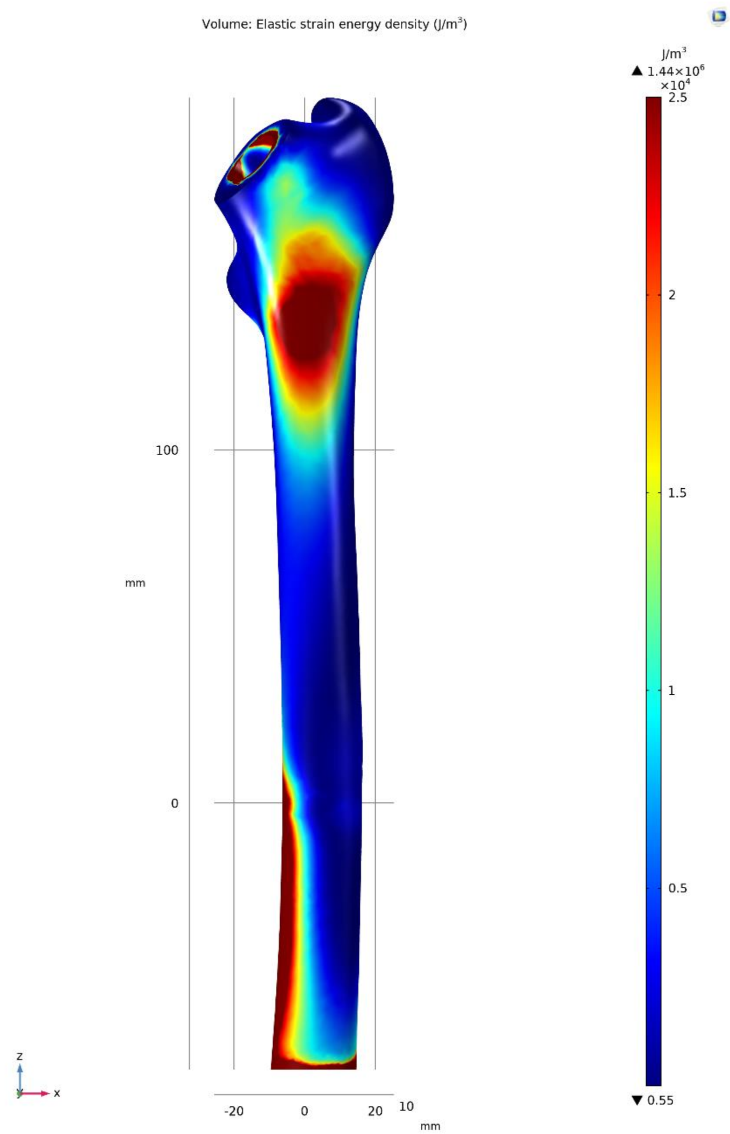

Figure 15

MOP model

This model gives an insight into the hidden aspect of the one causes of more failure rate associated with the usage of polymers in arthroplasties. It should be emphasized that the Poisson`s ratio of the UHMWPE in conjunction with its modulus of elasticity gives it more suboptimal performance not just its effect due to wear and tear.

The effect of the mechanical properties is direct on the bone while the effect of the wear is indirect that highlights the importance of judicious material selection.

In the next models, we had revealed a cross-section of some models to reveal the strain energy distribution inside of the bone structure and along the walls of the femoral bone.

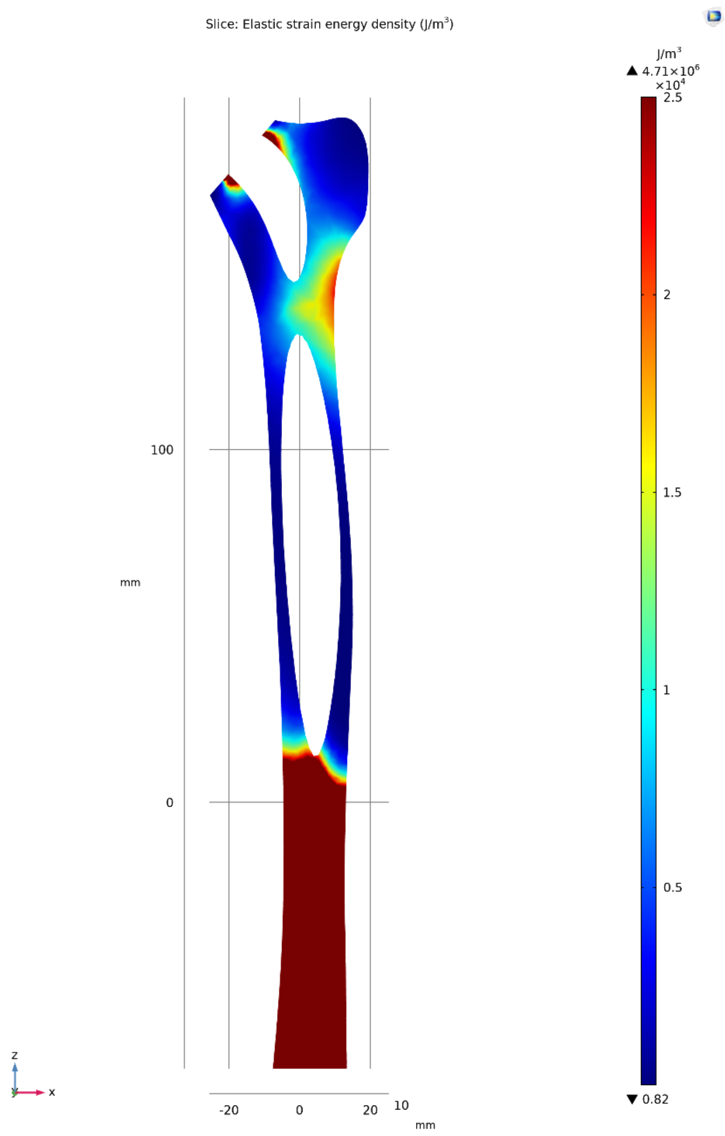

Figure 16

All ceramic model

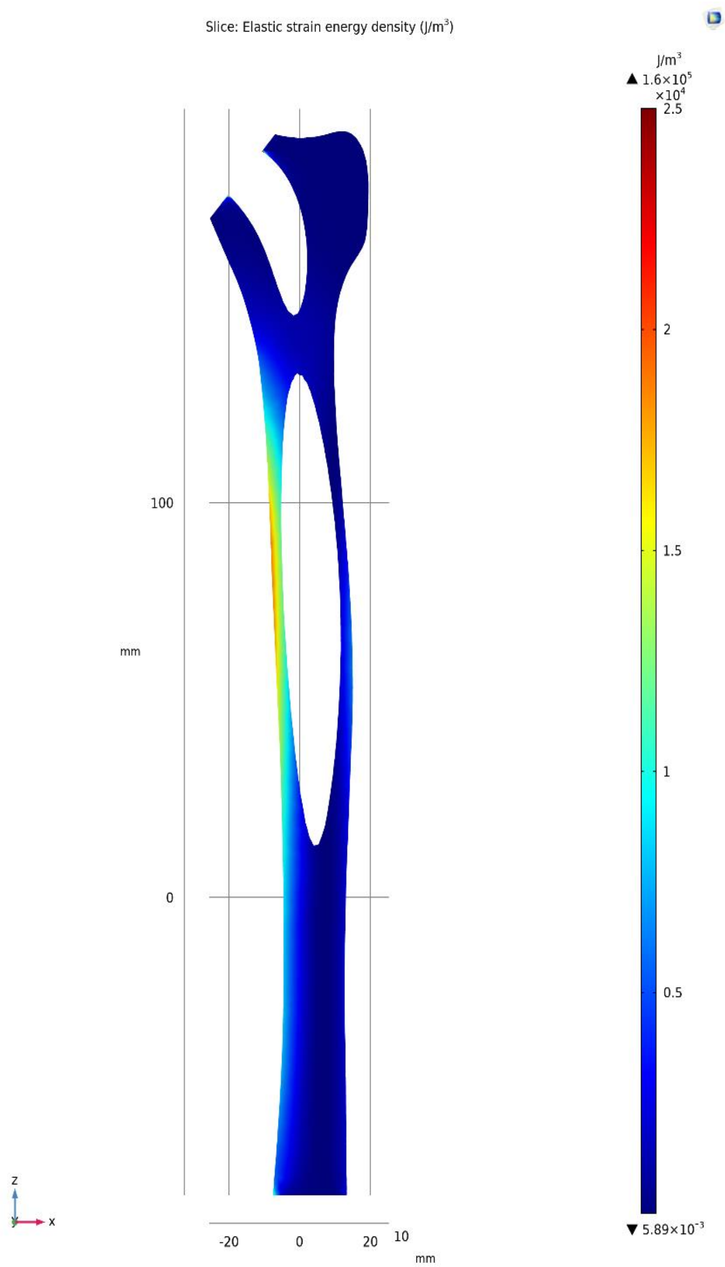

Figure 17

All polymer model

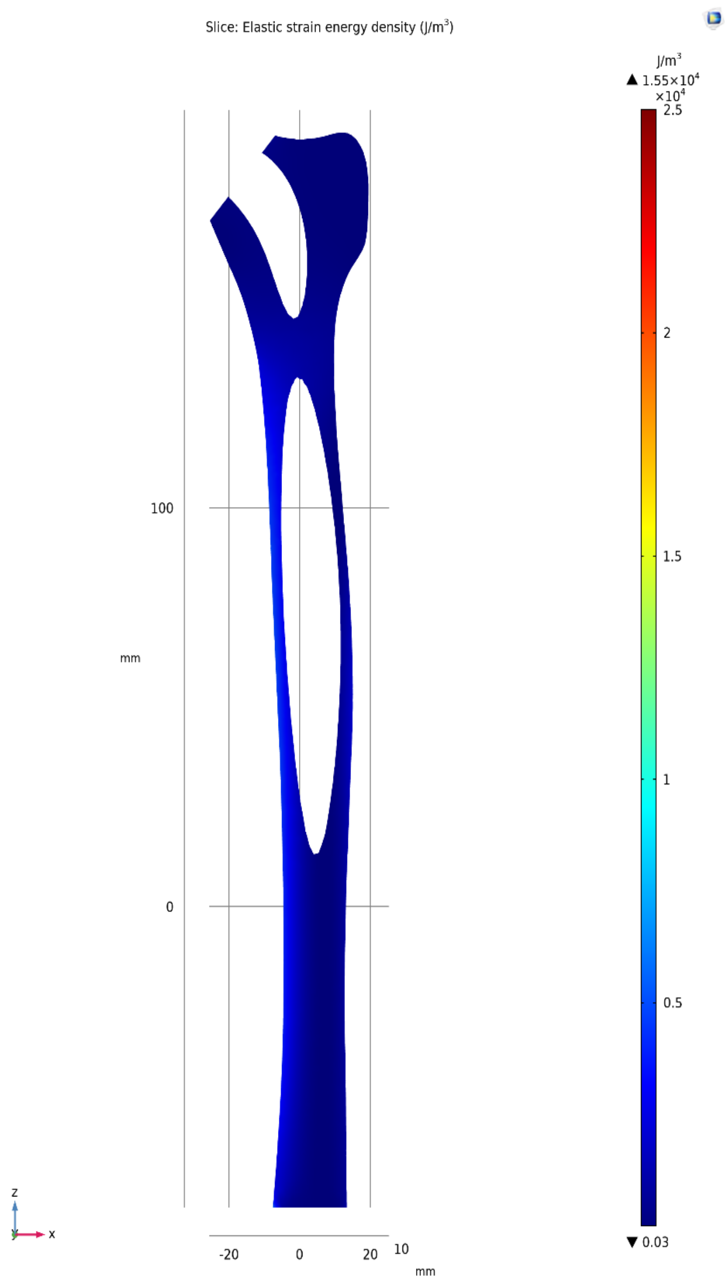

Figure 18

Normal bone model

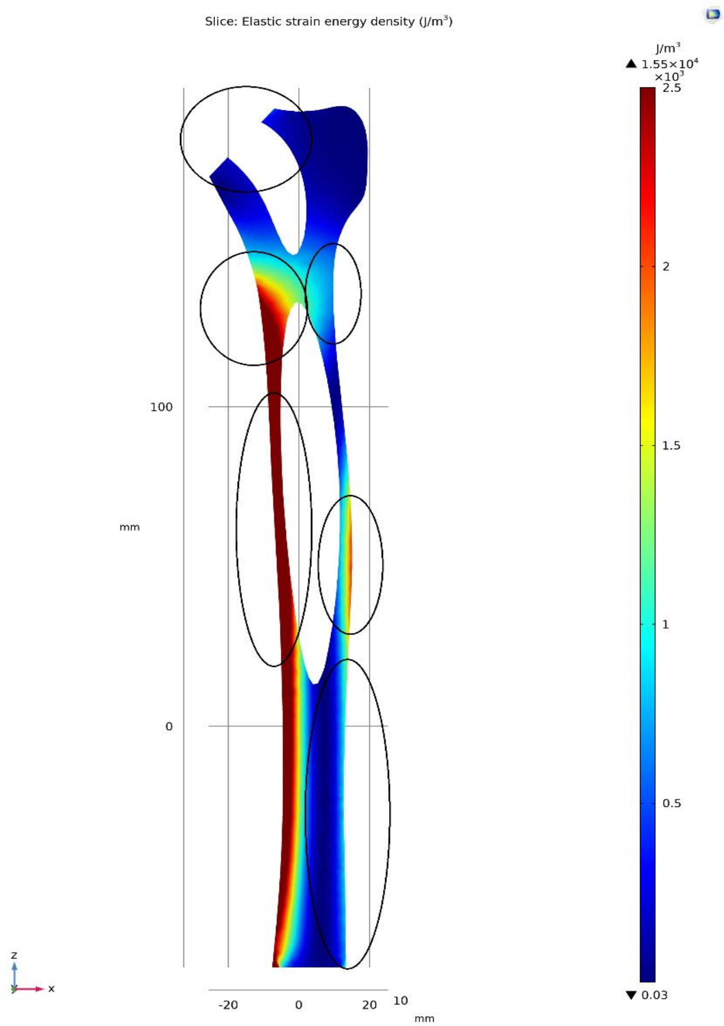

Figure 19

The normal bone model with manipulated values. The contrast between the bone model and the all-ceramic model is clear in the encircled regions

Conclusion

- Stress shielding is a devastating phenomenon. Its occurrence will be in the coincidence of stress concentration that leads to overcorticalization.
- The gradient of stiffness is an important matter that determines hardware biocompatibility.
- When the results of the FEM are reviewed after careful inspection of them, which is an unbiased tool, explains a current situation, it could be used to predict new rules. This is called the parametric approach

References

1. Murphy NJ, Eyles JP, Hunter DJ. Hip Osteoarthritis: Etiopathogenesis and Implications for Management. (1865-8652 (Electronic)).
2. Gademan MG, Hofstede SN, Vliet Vlieland TP, Nelissen RG, Marang-van de Mheen PJ. Indication criteria for total hip or knee arthroplasty in osteoarthritis: a state-of-the-science overview. (1471-2474 (Electronic)).
3. Brotto M, Bonewald L. Bone and muscle: Interactions beyond mechanical. (1873-2763 (Electronic)).
4. Escamilla RF, Macleod Td Fau - Wilk KE, Wilk Ke Fau - Paulos L, Paulos L Fau - Andrews JR, Andrews JR. Anterior cruciate ligament strain and tensile forces for weight-bearing and non-weight-bearing exercises: a guide to exercise selection. (1938-1344 (Electronic)).
5. Grover K, Hu M, Lin L, Muir J, Qin YX. Functional disuse initiates medullary endosteal micro-architectural impairment in cortical bone characterized by nanoindentation. (1435-5604 (Electronic)).
6. Denard PJ, Raiss P, Gobezie R, Edwards TB, Lederman E. Stress shielding of the humerus in press-fit anatomic shoulder arthroplasty: review and recommendations for evaluation. (1532-6500 (Electronic)).
7. Mukherjee K, Gupta S. Combined Bone Ingrowth and Remodeling Around Uncemented Acetabular Component: A Multiscale Mechanobiology-Based Finite Element Analysis. LID - 10.1115/1.4037223 [doi]. (1528-8951 (Electronic)).
8. Chen XA-O, He KA-OX, Chen ZA-O. A Novel Computer-Aided Approach for Parametric Investigation of Custom Design of Fracture Fixation Plates. (1748-6718 (Electronic)).
9. Gwam CU, Mistry JB, Mohamed NS, Thomas M, Bigart KC, Mont MA, et al. Current Epidemiology of Revision Total Hip Arthroplasty in the United States: National Inpatient Sample 2009 to 2013. (1532-8406 (Electronic)).
10. Karachalios T. Bone-Implant Interface in Orthopedic Surgery: Basic Science to Clinical Applications: Springer London; 2013.
11. COMSOL Multiphysics® v. 5.4 [Available from: www.comsol.com.
12. [Available from: http://www.matweb.com.
13. Weinans H, Huiskes R, Grootenboer HJ. The behaviour of adaptive bone-remodelling simulation models. Journal of Biomechanics. 1992;25(12):1425-41.
14. Zhang L, Sugamori KS, Claridge C, Dela Cruz A, Grynpas MD, Mitchell J. Overexpression of Gα(S) in Murine Osteoblasts In Vivo Leads to Increased Bone Mass and Decreased Bone Quality. (1523-4681 (Electronic)).
15. Unnanuntana A, Rebolledo Bj Fau - Khair MM, Khair Mm Fau - DiCarlo EF, DiCarlo Ef Fau - Lane JM, Lane JM. Diseases affecting bone quality: beyond osteoporosis. (1528-1132 (Electronic)).
16. von Engelhardt LV, Hahn M, Schulz T, Peikenkamp K, Jerosch J. Changes of the bone structure after cap resurfacing arthroplasty of the humeral head. (1877-0568 (Electronic)).
17. Pollock M, Somerville L Fau - Firth A, Firth A Fau - Lanting B, Lanting B. Outpatient Total Hip Arthroplasty, Total Knee Arthroplasty, and Unicompartmental Knee Arthroplasty: A

Systematic Review of the Literature. LID - 01874474-201612000-00004 [pii] LID - 10.2106/JBJS.RVW.16.00002 [doi]. (2329-9185 (Electronic)).

18. Sonntag R, Kretzer JP. Materials For Total Joint Arthroplasty: Biotribology Of Potential Bearings: World Scientific Publishing Company; 2015.
19. Maloney WJ, Sychterz C, Bragdon C, McGovern T, Jasty M, Engh CA, et al. The Otto Aufranc Award. Skeletal response to well fixed femoral components inserted with and without cement. Clin Orthop Relat Res. 1996(333):15-26.
20. Apostu D, Lucaciu O, Berce C, Lucaciu D, Cosma D. Current methods of preventing aseptic loosening and improving osseointegration of titanium implants in cementless total hip arthroplasty: a review. (1473-2300 (Electronic)).
21. Lachiewicz PF, Kleeman Lt Fau - Seyler T, Seyler T. Bearing Surfaces for Total Hip Arthroplasty. (1940-5480 (Electronic)).
22. Khanarian NT, Boushell Mk Fau - Spalazzi JP, Spalazzi Jp Fau - Pleshko N, Pleshko N Fau - Boskey AL, Boskey Al Fau - Lu HH, Lu HH. FTIR-I compositional mapping of the cartilage-to-bone interface as a function of tissue region and age. (1523-4681 (Electronic)).
23. Brodt S, Matziolis G, Buckwitz B, Zippelius T, Strube P, Roth A. Long-term follow-up of bone remodelling after cementless hip arthroplasty using different stems. Sci Rep. 2020;10(1):10143.
24. Yeoman M, Cizinauskas A, Lowry C, Vincent G, Collins S, Simpson D. Bone Remodeling Following Total Hip Replacement: Short Stem Versus Long Stem Implants2012.