Evaluating the performance of hollow stems used in total hip replacement by 3D finite element analysis

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Abstract. A 3D finite element analysis is carried out to evaluate the performance of our different developed hollow stems compared to the classical solid one. The hollow stems were developed considering the topology and shape optimization. Three types of optimized hollow stems were provided: KAD (Kharmanda-Antypas-Dyachenko) stem with a single hole, OAM (Optimized Austin-Moore) stem with double holes and IAM (Improved Austin-Moore) stem with three holes. A multi-objective formulation was developed as a performance scale for all kinds of studied stems (solid and hollow). This study is carried out according to the daily loading cases and considering that all used components (ball, stem, cortical and cancellous) are assumed to be made of isotropic and homogeneous materials. In the numerical applications, it is first shown the significant advantage of the three hollow stems compared to the solid one considering a performance function scale. Next, when comparing all hollow stems (KAD, OAM and IAM) in details, it is shown that the KAD stem for the daily loading cases, leads to the most homogeneous von-Mises stress distribution in both cortical and cancellous tissues.

1 Introduction

The total hip replacement is considered the major success story in orthopedic surgery in the few decades; there is a big interest in extending research on hip joint even further. The natural stress distribution in the bone tissue of a femur is prone to significant changes after an artificial replacement [1]. The stress reduction in the bone while using high elastic modulus implants is considered as stress shielding. When using artificial joint replacement by high elastic modulus metallic implants, it causes stress shielding in the adjacent bone tissues which could produce considerable disuse osteoporosis, later leading to loosening of prosthesis. Therefore, it is highly recommended that the stress distribution in the bone adjacent to the prosthesis should be uniform in order to provide a physiologic stimulus for bone and prevent stress shielding and disuse osteoporosis. Furthermore, the minimum stress values in the implant-bone interface represents another concern; it should not be less than target values. This way several objectives should be considered in order to improve the

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prosthesis performance. To solve these problems, several optimization strategies have been developed to study the relation between the performance and the design of the cementless hip stems [2-5]. In the context of a multi-criteria optimization, Ruben et al. [6] presented a double objective formulation taking into account the initial stability of the femoral stem and the effect of stress shielding on bone adaptation after the surgery. An additive formulation was proposed with coefficient calibration techniques. However, in our works (Kharmanda [7]; Kharmanda et al. [8]; Kharmanda et al. [9]), a multiplicative form was proposed as an effective technique to compare between the solid and hollow stems.

One of the most known hollow stem is Austin-Moore (AM) stem. This stem, historically, has considered as a effective implant over the years in the management of femoral neck fracture in elderly. It is commonly used in hospitals and clinic because of its low cost and simple surgical procedure and satisfactory prognosis. In order to present an effective strategy in the hollow stems, the topology optimization process is considered as a conceptual design stage to sketch the layouts. Kharmanda [7] integrated the topology optimization into the solid stem and produced a hollow stem with three holes. It was called Improved Austin-Moore (IAM) stem. However, the half bottom of the IAM stem was considered structurally useless. So, two different layouts were proposed: Kharmanda-Antypas-Dyachenko (KAD) stem with a single hole [8] and Optimized Austin-Moore (OAM) stem with double holes [9].

In this work, the performance of three types of hollow stems are first compared with the solid one according to the daily loading cases and considering that all used components (ball, stem, cortical and cancellous) are assumed to be made of isotropic and homogeneous materials. Next, all hollow stems (KAD, OAM and IAM) are compared to each other considering a homogeneity scale of the von-Mises stress distribution in both cortical and cancellous tissues.

2 Methods

2.1 Model description

The studied solid and hollow stems are analyzed taking into account the surrounding layers (the bone tissues and the ball) as illustrated in Fig. 1. Fig. 1a shows a 3D geometrical model of the whole studied structure (all layers). Fig. 1b shows the stem with the cortical and cancellous tissues. Fig. 1c shows the stem with the cancellous tissue. Fig. 1d shows the solid stem. The hollow stems are considered from the resulting layouts of the previous works [7,8,9].

Fig. 1. 3D geometry for a) studied structure, b) stem and cortical and cancellous tissues, c) stem and cancellous tissue, and d) stem.

Figs 2a, b, c and d show the 2D geometrical models for the solid stem, the KAD stem [8], the OAM stem [9] and the IAM stem [7] respectively.

Fig. 2. 2D geometry for a) Solid stem, b) KAD stem [8], c) OAM stem [10], and d) IAM stem [8].

The finite element mesh consists of two types of nonlinear elements: solid elements (SOLID187 with 10-nodes) and contact elements (CONTA174 with 8-nodes). The volume values and numbers of elements and nodes are presented in Table 1 for all studied stem cases (solid and hollow).

Table 1. Volume values and numbers of elements and nodes of all studied stems with the other layers.

Case Type	Solid stem	KAD stem	OAM stem	IAM stem
Total Element	52071	45004	45502	45774
Solid element	34394	29164	29550	29776
Contact element	17677	15840	15952	15998
Nodes	61088	52685	53331	53891
Volume (m ³)	112.21×10 ⁻⁶	110.11×10 ⁻⁶	109.79×10 ⁻⁶	108.52×10 ⁻⁶

2.2 Mechanical Properties

The hip replacement success is directly related to the ability to transfer the load uniformly from the components to the surrounding bone tissues. According to Wolff's law, a region of the bone which is unloaded by the presence of the prosthetic components will undergo to resorption, which will lead to loosening and eventually loss of functionality of prostheses. Hence, the minimum stress value in the surrounding bone has to be kept above a certain threshold [7]. The value of the target minimum stress is related to the natural Strain Energy Density. The Strain Energy Density (SED) can be written as follows:

$$U_N = \frac{1}{2E} \sigma^2 \quad (1)$$

The natural SED is estimated at the periosteal bone surface as: $U_N = 5.03 \times 10^{-6}$ MPa [7]. On the basis of Equation 1, the value of the target stress can be calculated as:

$$\sigma_T = \sqrt{2EU_N} \quad (2)$$

To ensure long-term fixation, the minimum stress value in the surrounding bone tissues must be higher than the target value σ_T . The cortical tissue is assumed to be a homogeneous and isotropic material with Young's modulus $E = 17$ GPa and Poisson's ratio $\nu = 0.33$. The cancellous tissue is also assumed to be a homogeneous and isotropic material with Young's modulus $E = 386$ MPa and Poisson's ratio $\nu = 0.33$ [11]. The Young's modulus of titanium alloy of stem is considered to be: $E = 110$ GPa and Poisson's ratio to be: $\nu = 0.3$ [10]. The ball is made of ceramic alloy which is assumed to be a homogeneous and isotropic material with Young's modulus $E = 408$ GPa and Poisson's ratio $\nu = 0.27$ [9].

2.3 Boundary conditions

Three daily loading conditions of one-legged stance (L_1), extreme ranges of motion of abduction (L_2), and adduction (L_3) are considered, as shown in Fig. 3. The fixation is considered to be at the lower bone cut (on the cortical tissue) in order to avoid rigid-body motion [7].

Fig. 3. a) One-legged stance case (L_1), b) Abduction case (L_2), and c) Adduction case (L_3).

2.4 Performance Function

At this stage, the performance function relates five aims objectives [8,9,10]. The mathematical formulation can be written as follows:

$$Performance = \frac{Volume \cdot \prod_{l=1}^{L_n} (\sigma_{max}^l - \sigma_{min}^l)}{Compliance \cdot \sigma_{min}^{Met/Bone}}$$

(3)

where σ_{max}^l and σ_{min}^l are respectively the maximum and the minimum von-Mises stresses of the two bone tissues (cortical and cancellous). $\sigma_{min}^{Met/Bone}$ is the minimum von-Mises stresses of the metal/bone interface stress.

3 Results

For the first loading case L_1 , Figs 4a, b, c and d show the von-Mises stress distributions for the solid stem, the KAD stem, the OAM stem and the IAM stem, respectively.

Fig. 4. von-Mises stress distributions for a) Solid stem, b) KAD stem, c) OAM stem, and d) IAM stem, when considering L_1 .

Table 2 presents the numerical results for the solid and hollow stems when considering the first loading case L_1 .

Table 2. Numerical results for the solid and hollow stems when considering the first loading case L_1 .

Parameters	Solid stem	KAD stem	OAM stem	IAM stem
σ_{max}^{Cor} (MPa)	64.15	74.82	76.40	76.42
σ_{min}^{Cor} (MPa)	0.06	0.03	0.03	0.04
σ_{max}^{Can} (MPa)	4.23	4.94	5.05	6.01
σ_{min}^{Can} (MPa)	0.03	0.03	0.03	0.02
σ_{max}^{Met} (MPa)	130.73	142.91	174.34	159.70
σ_{max}^{Ball} (MPa)	100.20	125.47	136.81	130.22
$\sigma_{min}^{Met/Bone}$ (MPa)	0.06	0.07	0.04	0.06
Compliance (N.m)	3.99×10^{-4}	7.82×10^{-4}	7.82×10^{-4}	7.90×10^{-4}
$\prod_{l=1}^2 (\sigma_{max}^l - \sigma_{min}^l)$	2.70×10^{14}	3.67×10^{14}	3.83×10^{14}	4.58×10^{14}
Performance	1.27×10^9	0.75×10^9	1.26×10^9	1.02×10^9

For the second loading case L_2 , Figs 5a, b, c and d show the von-Mises stress distributions for the solid stem, the KAD stem, the OAM stem and the IAM stem, respectively.

Fig. 5. von-Mises stress distributions for a) Solid stem, b) KAD stem, c) OAM stem, and d) IAM stem, when considering L_2 .

Table 3 presents the numerical results for the solid and hollow stems when considering the second loading case L_2 .

Table 3. Numerical results for the solid and hollow stems when considering the second loading case L_2 .

Parameters	Solid stem	KAD stem	OAM stem	IAM stem
$\sigma_{\max}^{\text{Cor}}$ (MPa)	66.97	68.06	68.19	68.10
$\sigma_{\min}^{\text{Cor}}$ (MPa)	0.005	0.01	0.01	0.01
$\sigma_{\max}^{\text{Can}}$ (MPa)	9.80	10.30	11.97	12.31
$\sigma_{\min}^{\text{Can}}$ (MPa)	0.03	0.03	0.03	0.02
$\sigma_{\max}^{\text{Met}}$ (MPa)	135.39	147.48	174.57	161.73
$\sigma_{\max}^{\text{Ball}}$ (MPa)	111.25	137.75	152.60	141.28
$\sigma_{\text{Met/Bone}}^{\text{min}}$ (MPa)	0.05	0.10	0.07	0.07
Compliance (N.m)	8.62×10^{-4}	11.36×10^{-4}	11.39×10^{-4}	11.37×10^{-4}
$\prod_{l=1}^2 (\sigma_{\max}^l - \sigma_{\min}^l)$	6.54×10^{14}	6.99×10^{14}	8.14×10^{14}	8.37×10^{14}
Performance	1.87×10^9	0.70×10^9	1.10×10^9	1.08×10^9

For the third loading case L_3 , Figs 6a, b, c and d show the von-Mises stress distributions for the solid stem, the KAD stem, the OAM stem and the IAM stem, respectively.

Fig. 6. Von-Mises stress distributions for a) Solid stem, b) KAD stem, c) OAM stem, and d) IAM stem, when considering L_3 .

Table 4 presents the numerical results for the solid and hollow stems when considering the third loading case L_3 .

Table 4. Numerical results for the solid and hollow stems when considering the thirst loading case L_3 .

Parameters	Solid stem	KAD stem	OAM stem	IAM stem
σ_{MAX}^{Cor} (MPa)	120.15	107.33	107.31	108.27
σ_{min}^{Cor} (MPa)	0.09	0.04	0.04	0.04
σ_{MAX}^{Can} (MPa)	11.02	10.58	13.15	13.01
σ_{min}^{Can} (MPa)	0.03	0.03	0.03	0.03
σ_{Met}^{Met} (MPa)	57.03	90.52	92.22	90.56
σ_{Ball}^{Ball} (MPa)	74.16	75.67	75.46	75.29
$\sigma_{Met/Bone}^{Met/Bone}$ (MPa)	0.04	0.04	0.05	0.05
Compliance (N.m)	21.18×10 ⁻⁴	23.64×10 ⁻⁴	23.61×10 ⁻⁴	24.04×10 ⁻⁴
$\prod_{l=1}^2 (\sigma_{max}^l - \sigma_{min}^l)$	13.20×10 ¹⁴	11.30×10 ¹⁴	14.10×10 ¹⁴	14.00×10 ¹⁴
Performance	1.75×10 ⁹	1.43×10 ⁹	1.28×10 ⁹	1.23×10 ⁹

In order to compare between the different stem types, two comparisons are carried out. The first one concerns the performance scale for the different stems (solid and hollow). Fig. 7 shows a comparison of performance scale values for the solid and hollow stems considering the different loading cases.

Fig. 7. Comparison of performance scale values for solid and hollow stems considering the different loading cases.

The second one concerns the homogeneity scale between the three types of hollow stems. Fig. 8 shows a comparison of homogeneity scale values for the different hollow stems considering all loading cases.

Fig. 8. Comparison of homogeneity scale values for the different hollow stems considering all loading cases.

4 Discussion

In this work, a comparison between the solid stem and the different developed hollow stems is carried out in two levels. The first level is to compare the hollow stems with the solid one

in order to show their advantages, while the second level is to compare the different hollow stems to each other in order to select the best one. In Tables 2, 3 and 4, different output results can be found. For each loading case, the corresponding compliance values are almost similar for the different hollow stem types. Thus, the comparisons are carried out considering the other output parameters such as von-Mises stresses, performance and homogeneity scales.

Considering the maximum values of von-Mises stresses as failure indicators, the resulting maximum values of the maximum von-Mises stresses are found in the OAM stem ($\sigma_{\text{max}}^{\text{Met}}=174.34\text{MPa}$, $\sigma_{\text{max}}^{\text{Met}}=174.57\text{MPa}$ and $\sigma_{\text{max}}^{\text{Met}}=92.22\text{MPa}$), while the minimum values of the maximum von-Mises stresses in the solid stem ($\sigma_{\text{max}}^{\text{Met}}=130.73\text{MPa}$, $\sigma_{\text{max}}^{\text{Met}}=135.39\text{MPa}$ and $\sigma_{\text{max}}^{\text{Met}}=57.03\text{MPa}$) for all loading cases (L_1 , L_2 and L_3), as shown in Figs 4, 5 and 6 and presented in Tables 2, 3 and 4. It is previously mentioned in [10] that the half bottom of the IAM stem is considered structurally useless, while the third hole in that IAM stem may help reducing the maximum von-Mises stress values compared to the OAM stem for the three loading cases as shown in Figs 4, 5 and 6. For the three hollow stems, the KAD stem has the minimum values of the maximum von-Mises stresses in the stems ($\sigma_{\text{max}}^{\text{Met}}=142.91\text{MPa}$, $\sigma_{\text{max}}^{\text{Met}}=147.48\text{MPa}$ and $\sigma_{\text{max}}^{\text{Met}}=90.52\text{MPa}$). It has also the minimum values of the maximum von-Mises stresses in the balls ($\sigma_{\text{max}}^{\text{Ball}}=125.47\text{MPa}$ and $\sigma_{\text{max}}^{\text{Ball}}=137.75\text{MPa}$) for the first and second loading cases (L_1 and L_2), while almost similar value ($\sigma_{\text{max}}^{\text{Ball}}=75.67\text{MPa}$) for the third loading case (L_3), compared to the other hollow stems as presented in Tables 2, 3 and 4.

Considering the performance scale, it is concluded that the performance of all developed hollow stems is much higher than that of the solid stem. In Kharmanda [8], a 3D validation was carried out to show that the IAM stem has a good reduction of the performance function compared to the solid stem, while in Kharmanda et al. [9] and Kharmanda et al.[10], the validation was carried out considering only 2D models. There is a strong need to compare the different hollow stems to the solid one using 3D models, that is performed in the current work. Fig. 7 shows that each one of hollow stems has a good reduction of the performance scale values compared to the solid stem for all loading cases. The KAD stem has a good reduction of the performance scale values for the first and second loading cases (L_1 and L_2), while the IAM stem has a small reduction of the performance scale value for the third loading case (L_3) as shown in Fig. 7

Considering the homogeneity scale, a comparison between the different hollow stem are carried out here to select the best one. The KAD stem leads to the best values of the homogeneity scale in all loading cases as shown in Fig. 8. As result, it is recommended to use the KAD stem since it leads to the most homogeneous von-Mises stress distribution for all loading cases.

5 Conclusion

The integration of topology optimization into hip prosthesis design leads to an optimum hole distribution that increases the fixation reliability relative to the solid stems where the fixation occurs only with porous coated surfaces. Several kinds of hollow stems are generated according to the loading cases. The shape optimization shows the importance of optimum hole distribution in stem design. After having compared several output parameters, it is found that the KAD stem leads to the most homogeneous von-Mises stress distribution for all loading cases (L_1 , L_2 and L_3). As a perspective, it seems to be very important to develop a mathematical model describing the ingrowth of bone into holes during the healing period and evaluating its reliability. In addition, the uncertainty concepts should be integrated when considering more complex loading schemes that may appear in the real life events.

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