Prediction of Femoral Head Collapse in Osteonecrosis

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The femoral head deteriorates in osteonecrosis. As a consequence of that, the cortical shell of the femoral head can buckle into the cancellous bone supporting it. In order to examine the buckling scenario we performed numerical analysis of a realistic femoral head model. The analysis included a solution of the hip contact problem, which provided the contact pressure distribution, and subsequent buckling simulation based on the given contact pressure. The contact problem was solved iteratively by approximating the cartilage by a discrete set of unilateral linear springs. The buckling calculations were based on a finite element mesh with brick elements for the cancellous bone and shell elements for the cortical shell. Results of 144 simulations for a variety of geometrical, material, and loading parameters strengthen the buckling scenario. They, particularly, show that the normal cancellous bone serves as a strong supporting foundation for the cortical shell and prevents it from buckling. However, under the development of osteonecrosis the deteriorating cancellous bone is unable to prevent the cortical shell from buckling and the critical pressure decreases with the decreasing Young modulus of the cancellous bone. The local buckling of the cortical shell seems to be the driving force of the progressive fracturing of the femoral head leading to its entire collapse. The buckling analysis provides an additional criterion of the femoral head collapse, the critical contact pressure. The buckling scenario also suggests a new argument in speculating on the femoral head reinforcement. If the entire collapse of the femoral head starts with the buckling of the cortical shell then it is reasonable to place the reinforcement as close to the cortical shell as possible. [DOI: 10.1115/1.2187050]

Introduction

Osteonecrosis of the femoral head can lead to its collapse [1]. The ideal treatment should aim at the arrest of the progression of the disease in precollapse stages. Therefore, in the management of the precollapse stages, an appropriate structural reinforcement of the femoral head is essential and the development of a method for the prediction of the head failure is desirable. Careful biomechanical analysis using computer simulations can help to rationalize the development of this method and to optimize the head reinforcement reconstructive method based on the individualized osteonecrosis conditions.

Traditional biomechanical analysis of the femoral head in osteonecrosis rests upon the linear elasticity theory. For example, Brown et al. [2] considered a realistic 3D finite element model of the necrotic femoral head. They studied changes in stress due to core drilling and bone grafting. Comparing stress distributions in the various cases of bone reinforcement they concluded that the key element of the mechanical efficacy of the graft was attainment of direct mechanical contact with the subchondral plate. It is important that Brown et al. [2] made an ad hoc assumption regarding the joint contact pressure distribution without analyzing it numerically. The latter was done by Yang et al. [3] who considered the contact region between the femoral head and the acetabulum and treated it as a contact problem. Besides, they varied the size of the necrotic zone explicitly and showed that this size affected the failure criteria significantly. It is worth mentioning that the cited works as well as other works, which are referred to in Brown et al. [2], and Yang et al. [3] use the local pointwise failure criteria only.

The fact that the cortical shell of the femoral head is significantly stiffer than the underlying cancellous bone did not attract much attention yet. However, from the structural mechanics point of view the difference in the stiffness of the cortical and cancellous parts of the femoral head under both normal and necrotic conditions is important. This difference allows for consideration of the femoral head as an elastic cortical shell on an elastic cancellous foundation. This, in its turn, suggests the buckling of the cortical shell as a possible starting point of the overall head collapse. The purpose of the present study was to assess the cortical shell buckling scenario as a possible mechanism of the femoral head collapse at the various stages of osteonecrosis.

Methods

Structural analysis of the hip joint included two stages. At the first stage of the discrete element analysis (DEA), the shapes of the femoral head and the acetabulum were created from the visible human dataset [4] and the potential contact area for an individual was established from the corresponding anteroposterior radiograph data [5]. The radius of the spherical femoral head was 30 mm. The cartilage between the acetabulum and the femoral head was approximated by 4000 unilateral linear springs. In order to find the joint pressure distribution the acetabulum and the femoral head were assumed rigid. The loads at the joint were chosen as the hip contact forces during activities of daily living [6]; a quasistatic load at 10% gait cycle of the normal walking and another static load at 50% during sitting down [7]. The "sitting down" scenario means the position that one finds oneself in immediately prior to contacting a seat during a sitting activity. The nonuniform pressure distribution (Fig. 1) was obtained by using an iterative procedure of solving the nonlinear contact problem [5,7].

At the second stage of analysis, the hip pressure obtained from the DEA was inverted into a distributed load on the femoral head (Fig. 1) for the subsequent finite element (FE) analysis. The spatial finite element model used 6000 continuum brick elements for
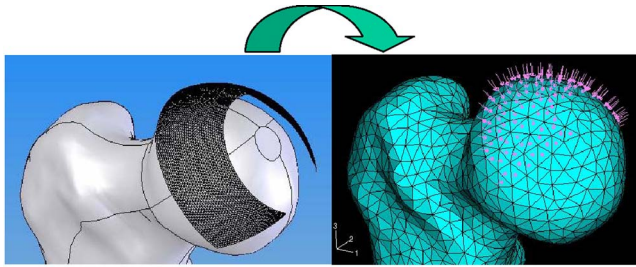
Fig. 1 Left: Discrete element mesh including 4000 unilateral linear springs, which mimic the cartilage, for the contact pressure derivation. Right: A schematic distribution of the contact pressure derived from the discrete element analysis. This pressure distribution is the initial load for the subsequent eigenvalue buckling analysis with the finite element method.
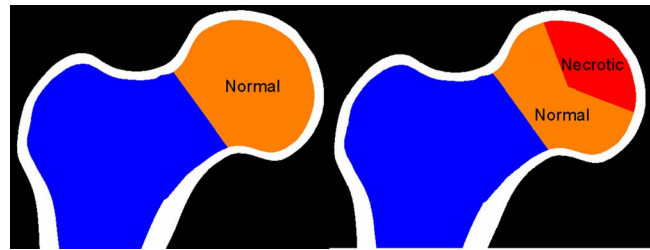

Fig. 2 Left: The intact femoral head model used in the finite element analysis. The head is fixed at the plane separating it from the femoral neck. Right: The femoral head with the necrotic zone in the form of a cone with the base angle of $2\pi/3$ rad. The necrotic zone has a lower value of the Young modulus than the surrounding intact cancellous bone.

the cancellous bone and 1000 triangular thin shell elements[3] for the cortical bone. The nodal points of the contacting brick and shell elements were properly adjusted not allowing for the displacement jump across the contact surface. The femoral head was rigidly fixed at the plane separating it from the femoral neck. The necrotic area was considered as a cone (Fig. 2) with the base angle of $2\pi/3$ rad [3]. ABAQUS [8] software was utilized for the eigenvalue buckling analysis (EBA) of the cortical shell under the normal and necrotic conditions.

The normal walking pressure (with the peak of 3.3 MPa, the average of 1.46 MPa, and the contact area of 76.3%) and the sitting down pressure (with the peak of 9.4 MPa, average of 1.59 MPa, and the contact area 17.6%) calculated from DEA [7] were used as the initial loads for the buckling analysis of the normal and necrotic femoral heads. The critical pressure obtained from the eigenvalue buckling analysis is a multiplication factor for the initial load to become critical. Isotropy was assumed for both cancellous and cortical bones and the Poisson ratio was chosen to be 0.25 for the cortical and 0.3 for the cancellous bone in all simulations. The Young modulus of the cortical shell was chosen to be equal to 1, 4, and 7 GPa while the cortical shell thickness was chosen to be equal to 1, 2, and 3 mm. The experimental data on elasticity and thickness of the intact cortical shell is lacking in the literature and we tried to cover a reasonable range of possible values of the Young modulus and the thickness. The Young modulus of the intact cancellous bone was chosen to be equal to 500 MPa. Under the developing necrosis conditions, this modulus was assumed to decrease to 400, 300, 200, 100, 50, 10, and 1 MPa within the cone shown in Fig. 2 mimicking the bone deterioration. It should be noted that the experimental data on the necrotic bone elasticity is quite restricted in the literature [9,10] and the need in such data is crucial.

Results

144 simulations of the eigenvalue buckling analysis were performed for a variety of geometrical and elastic parameters of the normal and necrotic femoral head under the static instants of normal walking and sitting down. The lowest positive eigenvalues indicating the critical pressure load are presented in Tables 1 and 2. Evidently, the deteriorating bone leads to the decreasing critical buckling pressure. A typical eigenmode distribution of the displacements normal to the femoral head surface, which correspond to the critical buckling load, is shown in Fig. 3 (left).

It is interesting that the sitting down process may be even more dangerous than the normal walking. The reason for that is the appearance of the relatively small contact area under the relatively high contact pressure (see also [7]).

Discussion

In the present work we performed structural analysis of hip joints with normal and necrotic femoral heads under normal walking and sitting down conditions. Results of the simulation show that the normal cancellous bone serves as a strong supporting foundation for the cortical shell and prevents it from buckling. This is not the case when osteonecrosis develops as it follows from the obtained results. The deteriorating cancellous bone is unable to prevent the cortical shell from buckling; the critical pressure becomes positive and its value decreases with the decreasing Young modulus of the cancellous bone. On the other hand, the deterioration of the cortical shell when the cancellous bone is already weak leads to further decrease of the critical buckling load. The local buckling of the cortical shell seems to be the driving force of the progressive fracturing of the femoral head leading to its entire collapse (Fig. 3 right). The proposed mechanism of the necrotic femoral head failure prompts a new criterion for the estimation of the femoral head strength, the critical buckling pressure. This criterion may aid the traditional pointwise strength criteria [2,11]. It is important to emphasize that the initial load for the subsequent buckling analysis was obtained from two quasistatic instants of real body motion conditions. Particularly, we considered the cases of normal walking and sitting down which are the worst from the point of view of contact hip pressure. These cases were identified by using DEA.

We split the structural analysis performed in the present work into solutions of two uncoupled problems. The first one is the determination of the contact pressure between the femoral head and acetabulum. The second one is the eigenvalue buckling analysis of the femoral head for the found distribution of the contact pressure. Such separation of two problems makes the entire analysis feasible. It is not without limitations, however. For example, computing the contact pressure we assume that both acetabulum and femoral head are rigid as compared to the soft layer of cartilage. This assumption is correct[4] and the cartilage is much softer than the cortical shell lying on the cancellous bone even in the case where the latter is necrotic. However, the stiffness ratio between the acetabulum and the femoral head is changing in the developing osteonecrosis and the account of the femoral head compliance can lead to a redistribution of the contact stresses. It would be interesting to assess this effect in the buckling analysis. Computationally this means a simultaneous solution of the nonlinear contact and buckling problems. The solution of the coupled

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[3]It should be mentioned that the use of the shell elements for the cortical bone modeling is not mandatory. Brick elements can also be used for the cortical shell; however, *one layer of the brick elements will not be enough* for estimating the critical buckling pressure of the femoral head under various necrotic conditions.

[4]In the case where there is no lesion in the cortical shell.

Table 1 Critical buckling pressure (MPa) during normal walking for the varying Young modulus of the cancellous bone and the varying thickness (3/2/1 mm) and Young modulus of the cortical shell

Cortical bone modulus	Cancellous bone modulus							
	500 MPa	400 MPa	300 MPa	200 MPa	100 MPa	50 MPa	10 MPa	1 MPa
7000 MPa	[a]						98.5	95.4
				89.4	66.9	54.9	44.8	42.5
	82.7	72.9	60.2	44.6	27.4	18.9	12.4	11.0
4000 MPa					91.0	74.8	61.1	58.0
			91.8	75.2	51.1	38.1	27.7	25.4
	76.5	68.2	57.7	42.9	24.1	14.8	7.9	6.5
1000 MPa	94.0	87.9	80.3	70.0	51.1	34.1	19.5	16.4
	79.0	72.5	64.6	54.0	35.9	21.2	9.4	7.2
	62.0	55.4	47.7	37.9	23.7	12.0	3.3	1.8

[a]No values indicate that the critical pressure causing femoral head collapse through buckling does not exist.

Table 2 Critical pressure (MPa) during sitting down for the varying Young modulus of the cancellous bone and the varying thickness (3/2/1 mm) and Young modulus of the cortical shell

Cortical bone modulus	Cancellous bone modulus							
	500 MPa	400 MPa	300 MPa	200 MPa	100 MPa	50 MPa	10 MPa	1 MPa
7000 MPa	82.0	79.1	75.4	70.5	63.5	58.6	53.5	52.2
	62.9	58.8	53.5	46.4	36.8	30.9	25.4	24.2
	41.6	36.7	30.7	23.1	14.5	10.2	6.9	6.2
4000 MPa	70.1	66.9	62.8	57.3	49.1	42.5	35.7	34.0
	55.5	51.6	46.4	39.3	29.1	22.5	16.3	14.9
	38.8	34.3	28.8	21.9	13.0	8.2	4.6	3.8
1000 MPa	48.6	45.2	41.2	36.0	28.2	21.0	12.2	10.3
	41.0	37.4	33.1	27.4	19.2	12.5	5.7	4.3
	32.9	29.1	24.5	18.9	11.5	6.6	2.0	1.1

contact-buckling problem can lead to the higher or lower critical buckling loads as compared to the uncoupled analysis presented in our work. The former can happen when the contact area is large (e.g., normal walking) and high pressure can be supported by the parts of the contact area that are located out of the necrotic zone. The latter can happen when the contact area is small (e.g., sitting down) and located within the necrotic zone. In the latter case, the acetabulum will play the role of a stiff indentor penetrating a soft femoral head.

Whatever the method of buckling analysis, the linear eigenvalue computations or a more sophisticated technique, it is important to emphasize that instability of the cortical shell should be considered as a possible indicator of the overall head collapse.

This is the main message of the present work. Numerous clinical observations give clear evidence of the existence of the buckled areas on the surface of the collapsed femoral heads.

We should emphasize, however, that the cortical shell buckling is not necessarily the only possible scenario of the initiation of cracks and the overall collapse of the femoral head. Alternatively, the nucleation and development of the fatigue cracks can lead to the collapse of the femoral head before the cortical shells buckles. It is also possible that the elastic buckling and the fatigue cracking compete in the process of the femoral head collapse.

The proposed mechanism of the femoral head failure provides a new qualitative argument for the reinforcement of the necrotic femoral head. If the entire collapse of the femoral head starts with the buckling of the cortical shell, when the cancellous bone is already deteriorated, then it is reasonable to reinforce the cortical shell by a supporting structure. Such structure should be placed as close to the cortical shell as possible in order to prevent bending and buckling of the shell. The precise placement of the reinforcement will require detailed information about the necrotic area in every specific case [12,13].
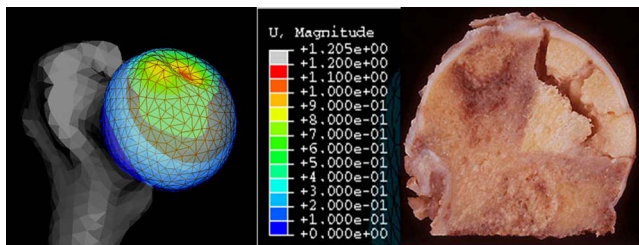

Fig. 3 Left: A typical buckling mode in the form of the surface cavity. ABAQUS simulation with 6000 continuum brick elements for the cancellous bone and 1000 thin shell elements for the cortical bone. The nodal points of the contacting brick and shell elements were properly adjusted not allowing for the displacement jump across the contact surface. Right: Sample femoral head after collapse.

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