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Computer simulation on fatigue behavior of cemented hip prostheses: a physiological model

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Summary This paper is concerned with the investigation on the fatigue failure of implant fixation by numerical approaches. A computer algorithm based on finite element analysis and continuum damage mechanics was proposed to quantify the fatigue damage rate of cement mantle under physiological conditions. In examining the interfacial debonding effect, the interface elements were introduced at cement—stem interfaces and calibrated with the increase of loading cycles.

Current results reveal that the major sites for failure initiation are in the proximal anterior-medial regions and at the distal prosthesis tip, which clearly demonstrate the same failure scenario as observed in clinical studies. Such fatigue failures not only result in the corruption of cement—stem interfaces, but also greatly affect the cement stress distribution and the damage rate in subsequent loading cycles. Another significant result is that the predicted damage rate increases steadily with gait cycles. This trend in damage development is consistent with the findings obtained from fatigue tests available in literature. It is anticipated that presented methodology can serve as a pre-clinical validation of cemented hip prostheses.

1. Introduction

Of the total hip joint replacements, the cemented fixation method was mostly adopted owing to offer the immediate stability from cement—stem and cement—bone bonding interface after implant surgery. However, clinical studies also reported that the cemented hip prostheses failed to function properly due to the loosening of fixation after long-term use. Based on the retrieval studies, Jasty et al. [1,2] had identified that such failure of fixation was initiated by the debonding of cement—stem interface and local fractures in the cement mantle. From the microscopic examination on fracture surfaces of retrieved cement mantle, Topoleski [3] and Culleton et al. [4], respectively, demonstrated that these fracturing modes could be regarded as a type of fatigue failure of bone cement.

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For the long-term durability of a cemented total hip prosthesis, a number of researchers, with the realization onto the failure mechanism, had proposed great improvements in prosthetic design. However, before clinical applications of any new prosthetic implant, the pre-clinical validations on the performance of integrated femoral components against these failure processes are essential. For this, the experimental approaches have been greatly adopted, in which the ISO 7206 standard for fatigue failure test is followed. As a comparative investigation, the experimental work requires physical implant models and replicates the loading configurations. However, this is usually inflexible in facing the design changes. In addition, the consuming in time or cost is further needed to take into considerations.

To cope with these limitations, mechanical analysis is practically an effective approach in investigating the fatigue behaviors of cemented hip prostheses under physiological conditions. In this paper, a computer algorithm was proposed to quantify the fatigue damage of the cement mantle bonding the bone and prosthetic implant. Through this simulation, parametric study on factors affecting the fatigue failure can thus be clarified and investigated.

2. Background

Apart from experimental investigation, finite element methods have been used to investigate the effect of the cement—stem bonding conditions on stress variations within cement mantle [5—7] and fatigue failure of cemented hip prostheses [8—10]. Concerning the cement damage, Verdonschot and Huiskes [8], Stolk et al. [9] and Colombi [10], respectively, applied the continuum damage theory to evaluate the fatigue damage of cemented hip prostheses under simplified loading configurations. In these numerical approaches, the interface between cement and stem was assumed either in completely bonded or debonded conditions. To simulate the debonding of the cement—stem interface, the Coulomb friction elements with various friction coefficients [6,11] were usually introduced over the entire interfaces. As a result, similar cement failure scenario was found but with different growth rates in damage development. However, further comparison on the results from numerical predictions and experimental investigations showed great differences on the damage developing process existing among these results.

Actually, observations from fatigue experiments or clinical studies have demonstrated that the cement—stem interfaces breakdown at regions where local fractures of the cement mantle were initiated [2], and separation of the interface gradually spread out with the propagation of the damaged regions. Since the load transferred from stem to cement occurs primarily through the interfaces, the deterioration of interface bonding will affect the load-transferring path in the cement mantle. However, such effect on cement stress distributions and fatigue damages was not considered in previous numerical analysis.

This paper is concerned with the simulation of the fatigue behavior of cemented hip prostheses in more realistic manners. To this purpose, a physiological model of a cemented femur was first created. The progressively changed interface elements were further introduced into the femoral model to simulate the debonding of the cement—stem interface. Variations in cement damage rate under different bonding conditions were then evaluated and compared with the discoveries reported in literature.

3. Design considerations

3.1. Model formulation

3.1.1. Fatigue damage analysis

As declared by Verdonschot and Huiskes [8] and Colombi [10], the theory of continuum damage mechanics has the priority in investigating the fatigue damage accumulated in the cement mantle. According to the Palmgren—Miner linear damage rule [12], the fatigue damage accumulated in material under various cyclic stresses can be expressed as

$$D = \sum_{i=1}^{n} \frac{n_i}{N_{fi}} \quad (1)$$

in which N_{fi} is the fatigue life, or the number of cycles, to failure at stress amplitude σ_i, and n_i is the real loading cycles at that stress level. The fatigue life at specific stress level can be determined from stress-life data obtained in fatigue tests, which can be fitted as the Basquin equation [13] as well

$$N_f \sigma^k = C \quad (2)$$

where k and C are material parameters determined from the fatigue experiments. For centrifuged bone cement specimens, these values are reported as $k = 4.68$ and $\log C = 8.77$ [14]. Basically, Eq. (1) can then be used to predict whether fatigue failure occurs. However, since the majority of fatigue tests were conducted under uniaxial loading conditions, Eq. (1) is thus regarded as the accumulation of bulk damage within material under uniaxial stress state.

In practical applications, the three-dimensional hip prostheses are always subjected to complicated loadings, including bending and torsion effects. Under this condition, the fatigue damage of the bone cement should be considered to be generated in various directions where cracks may initiate and propagate. Such fatigue behavior is termed as multiaxial fatigue. As the bone cement has higher shear strength than tensile strength, cracks are prone to initiate in the direction of principal stress. Consequently, the damage accumulation at any point in the cement mantle should be defined by its local damage tensor $D_{i\mathrm{p}}$ in principal values

$$D_{\mathrm{ip}} = \begin{bmatrix} d_1 & 0 & 0 \\ 0 & d_2 & 0 \\ 0 & 0 & d_3 \end{bmatrix}_{\mathrm{ip}} . \tag{3}$$

In the above tensor in Eq. (3), d_i is the damage value in the principal direction, which can be assessed from Eq. (1). Cement cracks are assumed to initiate at regions where the local damage d_i in any principal direction reaches the critical value 0.95 [8]. The total damage accumulation within the whole cement mantle can then be evaluated by summing over all nodal points

$$D_{\mathrm{tot}} = \sum_{\mathrm{ip}=1}^{N_{\mathrm{ip}}} \sum_{i=1}^{3} (d_i)_{\mathrm{ip}} \tag{4}$$

where $N_{i\mathrm{p}}$ is the overall nodal points. To evaluate the critical damages accumulated within the cement mantle, the term critical damage rate is used as the failure index representing the percentage of the cement mantle being damaged to failure after certain number of loading cycles. Through the implementation of these equations, the fatigue failure behavior developed in the cement mantle and cement—stem interface can then be quantified.

3.2. Finite element modeling

A three-dimensional FE model of a non-cemented hip prosthesis created from previous study [15] is modified into an idealized proximal femur with cemented metallic stem, as shown in Fig. 1. The cemented femoral model consists of the stem, the cement mantle and the compact bone, in which only the compact bone is modeled because most of the cancellous bone is drilled out to allow for cementing metallic stem. Owing to this, the residual compact bone is considered as linearly isotropic and homogenous although the human proximal femur, especially cancellous bone, exhibits transversely isotropic behavior with the properties depending on the direction and location. The cross-section of the cement

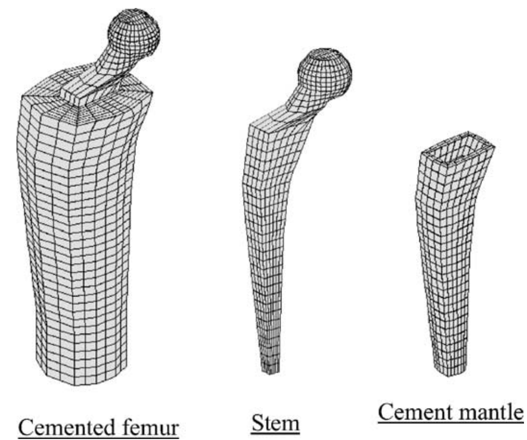

Fig. 1 Three-dimensional finite element model of proximal femur cemented with stem. *F*1: Iliopsoas muscle force; *F*2: gluteal muscle force; *F*3: abductor force; *F*4: Iliotibalis muscle force; *F*5: joint reaction force.

mantle varies with the stem shape from proximal to distal, but with constant thickness of 4.0 mm [8], which is within the ideal thickness range of 2—5 mm for clinical use [16]. The whole model is meshed with hexahedron brick elements and contains 6920 elements and 7716 nodes. In addition, the interfaces between bone and cement are assumed to be firmly bonded since the retrieved cemented components had shown the interface was well fixed [2]. The interface elements [17] are added at the interface between the stem and the cement to simulate various bonding conditions. The material used for metallic stem is titanium alloy Ti—6Al—4V with Young's modulus 110 GPa; the compact bone and PMMA cement have Young's modulus 18.6 GPa and 2.28 GPa, respectively. All the materials have the same Poisson's ratio $\nu = 0.3$ [6].

In order to simulate the fatigue damage to the cement mantle under normal walking conditions, the physiological femoral loadings are imposed on the femur model. Generally, the femoral loadings including the joint forces and muscle forces (abductors and adductors) are generated during the stance phase (from heel-strike to toe-off) of the gait. According to the gait analysis by Paul [18] and Marrison [19], for a girl of body weight 54.3 kg, the force components at different gait percentages of 2, 13, 19, 50 and 63% are listed in Table 1 and their loading directions and positions are shown in Fig. 2. Such loading conditions with bending, torsional and compressive effects can be thought of being more physiological than those used in other researches [8—10]. These gait loadings are then divided into five loading modes and applied on the femoral model with different loading directions for subsequent stress analysis, respectively.

Table 1 Force components acting on the femoral model, including joint forces, muscle forces varying the gait phase

Force components		Percentage of gait phase				
		2%	13%	19%	50%	63%
*F*1	*Fx*	0	133	172	173	177
	Fy	0	31	39	26	19
	Fz	0	155	199	213	161
*F*2	*Fx*	−11	0	0	0	0
	Fy	45	0	0	0	0
	Fz	262	0	0	0	0
*F*3	*Fx*	96	281	334	256	0
	Fy	62	148	141	−68	0
	Fz	82	230	283	289	0
*F*4	*Fx*	0	0	0	0	0
	Fy	0	0	0	0	0
	Fz	−42	−29	−34	−29	0
*F*5	*Fx*	−429	−552	−562	−488	−140
	Fy	61	−225	−130	329	14
	Fz	−399	−1110	−1075	−1137	−433

*F*1: Iliopsoas muscle force; *F*2: gluteal muscle force; *F*3: abductor force; *F*4: Iliotibalis muscle force and *F*5: joint reaction force.

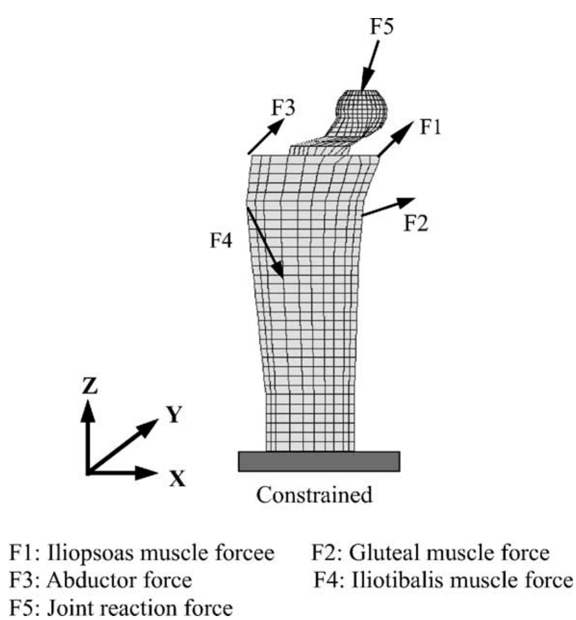

Fig. 2 Schematic representation of gait loadings acting on the femur, including joint forces and muscle forces. The force components varying with gait phase are listed in Table 1. The boundary condition applied on the FE model is shown in the figure.

4. System descriptions

Clinically, the fatigue behavior is a time-related scenario and the deterioration of the bonding interface initiated by fatigue damage eventually reduces the load-carrying capability from stem to cement and bone, leading to the stress redistribution within the cement mantle. To imitate the change in bonding status, the cement—stem interfaces are considered to breakdown at critical locations where fatigue damage accumulations reach the defined critical value. The interface bonding conditions are thus modified from initially firmly bonded into partially bonded status according to the interface failure sizes. Based on the above considerations, the simulation algorithm is developed and illustrated as follows.

1. Construct an initial FE model of a cemented hip prosthesis.
2. Define five loading modes corresponding to five gait phases within one gait.
3. Perform stress analysis for each loading mode respectively, which constitutes the stress cycle in one gait.
4. Loop in the iteration for estimating the damage rate after a given number of loading cycles.
   (i) Calculate the local damage tensor D_{ip} in principal stress directions for each nodal point.
   (ii) Estimate the critical damage rate accumulated within the cement mantle by summing up all the nodal points with local

damage reaching the critical value, which are marked as the damaged region.
(iii) Check whether the designated simulation cycle is reached or not. If not, proceed to step 4, else go on step 5.
5. Calibrate the FE model with appropriate interface bonding conditions according to the interfacial failure sizes.
6. Proceed to step 2 for subsequent simulations.

The system of the current algorithm is operated as an iterative process and the overall programs coded in FORTRAN with 64-bit data precision consist of two parts: three-dimensional stress analysis, and fatigue damage assessment. In stress analysis, a previously developed package FEAST[1] was modified for running on a personal computer. Results of the FE analysis are then served as the input for subsequent fatigue simulation.

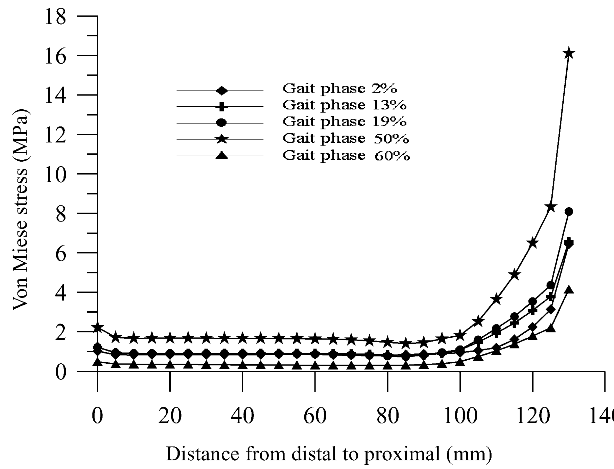

Fig. 3 Variation of cement stresses at different gait phase, showing higher stress induced around proximal end of femur and the peak stress occurring at gait phase of 50%.

5. Status report

In this paper, three different bonding conditions for cement—stem interfaces are presented to investigate their effects on the fatigue behavior of cemented hip components. For the first mode, the cement—stem interfaces were modeled as firmly bonded, transferring all the forces from stem to cement and bone, and two different stem materials (titanium and CoCrMo) were employed to assess the effect of the stem stiffness on cement damage. In the second mode, the bone cement was assumed to separate from the stem proximally but the other regions were still in bonded status. Such a separation at the proximal interface was specified with a debond length measured from the incision of the femur. In the third mode, the progressively debonded interfaces were introduced into femoral model to simulate the deterioration of the bonding with loading cycles. This mode is of great significance in evaluating the long-term performance of cemented hip prostheses under physiological conditions.

5.1. Stresses in cement

Before fatigue simulation, FE stress analysis was performed to assess the stress state of cemented hip prostheses in overall under physiological gait loadings. These results are presented as von Mises stresses [20], which give an indication of the stress level induced in the cemented prostheses. Fig. 3 shows the variation of the maximum von Mises stresses in the cement mantle along the longitudinal direction of stem, which are predicted at different gait phases, respectively. It is observed that the proximal cement show higher stress than other regions. In addition, the overall cement stresses come to a maximum value at the fourth loading mode (50% of gait cycle). Distributions of the cement stresses around proximal stem are further demonstrated by shaded image depicted in Fig. 4. In the figure the higher stressed regions mainly concentrate at the medial proximal portion of cement mantle, and a lesser extent in the lateral regions. The magnitude of the maximum tensile stress in these regions is about 5.8 MPa, which is well below the tensile strength of bone cement. The ultimate tensile strength of commercial acrylic bone cement available in literatures is reported from 35 to 45 MPa [21] and 31.7 to 51.4 MPa [22], respectively, whereas the fatigue strength is only 8—10 MPa [23]. Results of stress analysis further imply that the primary mechanism controlling the failure of cemented hip prostheses is the local cement fatigue failures, especially, at the regions with highest stresses [6,24].

5.2. Validation of fatigue simulation

Two different cement—stem interfacial bonding conditions were presented to validate the fatigue simulation algorithm by comparing the predicted results with those available in literatures. For the first mode, the cement—stem interfaces are main-

[1] Finite element analysis of structure (FEAST), 1993, a software package which regulates the information storage and retrieval of literature reference of the database of the system MAKEBASE developed by J.S.S. Wu and distributed by Department of Mechanical Engineering, Linkoping Institute, Sweden.

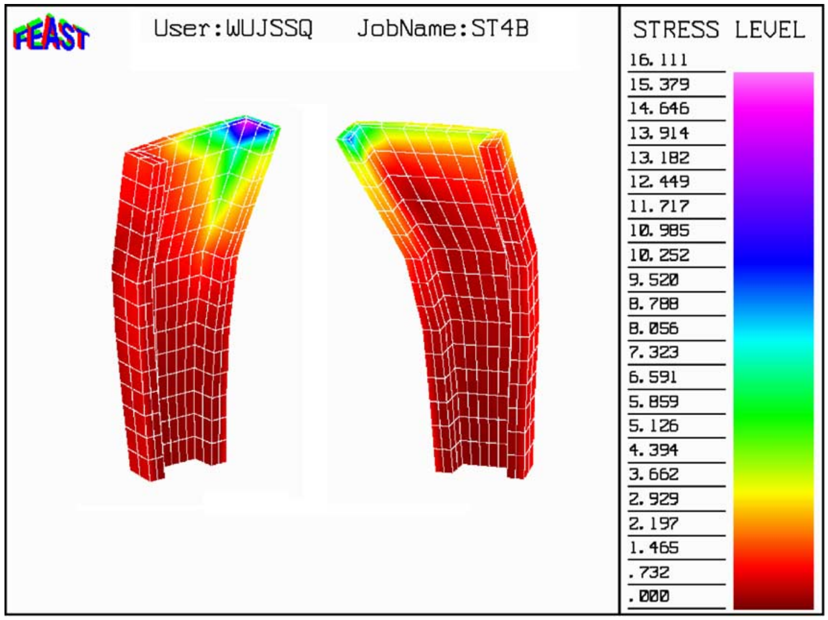

Fig. 4 Shaded image of von Mises stresses around proximal cement, which was predicted at gait phase of 50% generating a maximum loading effect on femur.

tained in completely bonded status during the loading stages. Under physiological conditions, the predicted damage rate of the cement mantle is expressed as a function of the loading cycles and shown in Fig. 5. It can be seen from Fig. 5 that the growth rate of the fatigue damage is rapid and significant at early loading stages, but it gradually slows done in subsequent gait cycles. To get insight into the fatigue behavior more clearly, Fig. 6 illustrates the development of the damaged region shaded with purple color within the cement mantle, where fatigue cracks are considered to initiate. Current results clearly indicate that the most likely sites for failure initiation are in the proximal anterior-medial regions and at the distal prosthesis tip, and then the damaged regions gradually propagate toward the medial portions in the longitudinal and the radial directions. Such fatigue scenario is obviously consistent with the observations on

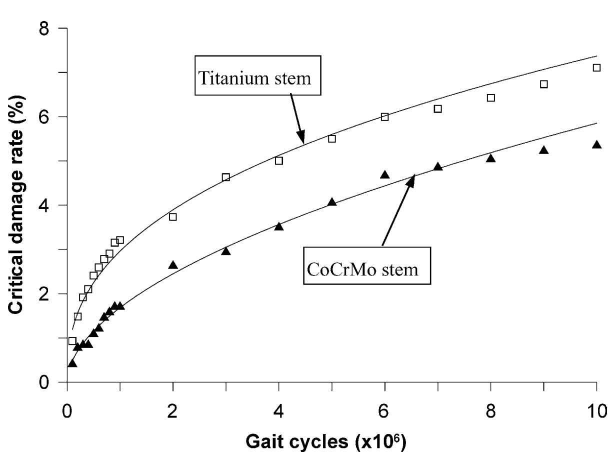

Fig. 5 Accumulation rate of critical damage within cement mantle as a function of gait cycles. These data were predicted for femoral models with a fully bonded interface between metallic stem and bone cement. The effect of stem stiffness on cement damage is also shown in this figure.

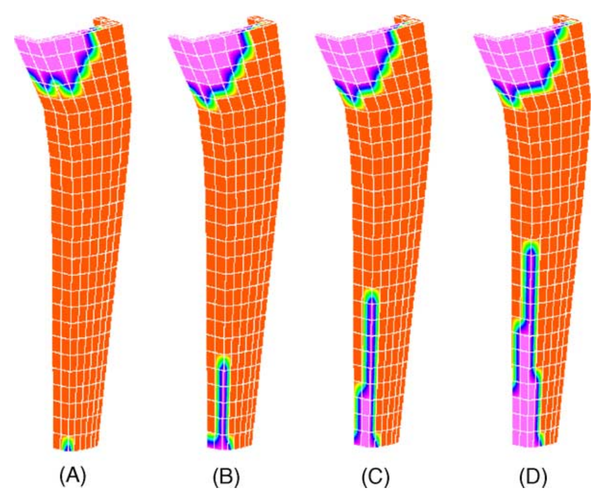

Fig. 6 Damage patterns of the cement mantle after 6, 12, 20 and 30 million loading cycles (from left to right). Damaged regions are shaded with purple colors. Fatigue damages were assessed for proximal femur cemented with titanium stem. A fully bonded cement—stem interface was assumed for this model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

physical models used in fatigue tests [25,26]. Additionally, as revealed in retrieval studies [1,4], fatigue cracks often originated from the stem surface. This might be associated with the sharp corners in the stem geometry where high stresses were found. It is believed that the abrupt change in geometry of stem may cause high stress concentration in local area and hence initiates the fatigue failure [27].

The effect of the stem stiffness on cement damage rate can also be investigated by this mode. As seen in Fig. 5, at first 10 million gaits, the femur cemented with titanium stem creates higher cement damage rate (7.4%) than that with CoCrMo stem (5.4%), approximately difference (1.9%). At proximity a stiffer stem transfers less stress to the cement mantle and thereby lowers the cement damage rate, but this effect is very small. This tendency agrees well with the results reported by Colombi [10].

In contrast to the first case, Fig. 7 shows the effect of proximal interface separation on the damage rate of bone cement. The predicted cement damage rates after 10 million gait loadings are 8.6%, 8.8%, 9.5% and 12.3% for femoral model with assumed debonded length of 5, 10, 15 and 20 mm around the proximal stem, respectively. These values are higher than that generated for perfect bonded cemented implant (7.4%). It is apparent that the local separation at proximal interfaces causes more damages to cement mantle, and hence the risk of fixation failure. Moreover, such effect enhanced as the debonded region is deepened. Similar prediction is also shown in the study conducted by Stolks, et al. [9]. In their investigations, the number of crack was used to evaluate the accumulation of fatigue damage within cement mantle and the debonded interface was found to induce more cement cracks than fully bonded interface. In other words, this observation revealed that the cemented hip prostheses yielded higher cement damage rates owing to the corruption of the interface bonding.

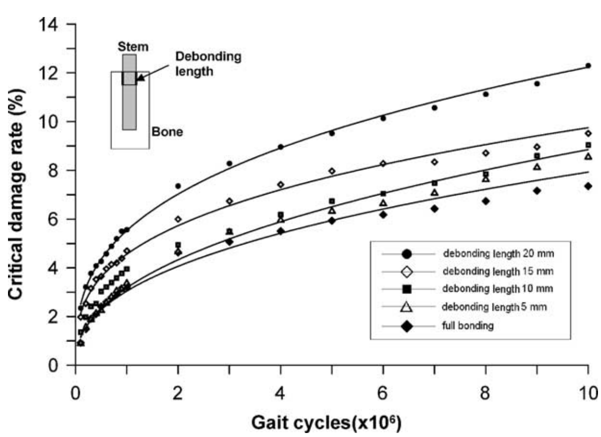

Fig. 7 Accumulation rate of critical damage within the cement mantle as a function of gait cycles. These data were predicted for femoral models with proximal separation at cement—stem interface. Such a separation was specified in terms of the debonding length (5, 10, 15 and 20 mm), respectively.

5.3. Progressive fatigue behavior

As revealed in clinical studies [1,2], the fatigue cracks originated within cement mantle and stem surface had led to the localized separation between cement and stem. It followed that more cement mantle were damaged to fracture owing to the progressive debonding at the cement—stem interface in subsequent loading. This is believed to be the main mechanism dominating the failure of the fixation of cemented hip prostheses. In order to implement such perception into fatigue simulation, the progressively debonded interfaces in localized regions around the stem are introduced into the cemented femur model. The real fatigue behavior of the cement mantle accompanied with interfacial debonding is thus identified from the results assessed in this mode. As shown in Fig. 8, the critical damage rates of the cement mantle steadily increase with the gait cycle, which not only exhibit a quite different fatigue behavior but it also derives great differences in cement damage rates than those predicted under the first two cases.

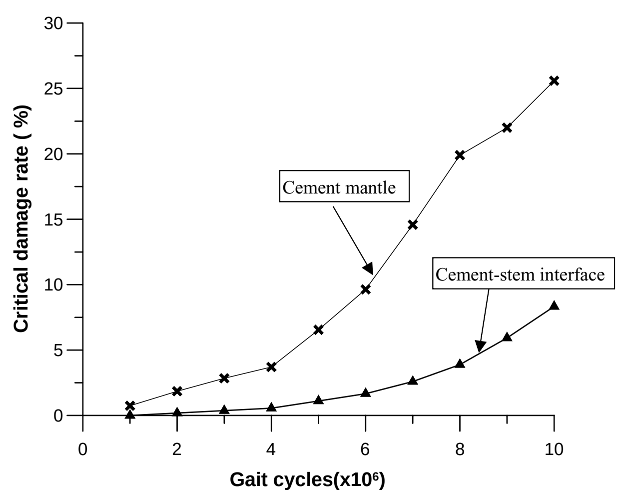

Fig. 8 Critical damage rates within the cement mantle and at the cement—stem interface as a function of gait cycles, showing different trend in damage development as that shown in Fig. 5. The data were assessed for femoral model with progressively debonded interfaces between stem and bone cement, and a titanium stem was cemented in femur.

Table 2 Stress variations within proximal cement mantle after a certain number of loading cycles

Gait cycles ($\times 10^6$)	Maximum tensile Stress (MPa)	Variations of cement stress (%)		
		Maximum tensile stress	Maximum shear stress	Maximum von-Mises stress
2	11.3	−3 to 93	−28 to 61	−27 to 58
4	12.0	−29 to 264	−47 to 153	−47 to 152
6	14.8	−80 to 285	−48 to 207	−48 to 203
8	25.3	−92 to 591	−75 to 162	−74 to 172

Results indicted that the maximum cement stress changed with gait cycles owing to the gradually debonding at the cement—stem interfaces. It is noted that the predicted maximum tensile stress for femoral model with fully bonded interfaces is 5.8 MPa.

It is encouraging to find such a damage initiation behavior in fatigue tests conducted by McCormack et al. [25]. In their work, the number of cracks initiated in cement mantle was used as a failure index to characterize the damage accumulation of cemented hip prostheses. Cracks were found to initiate continuously from the pore sites within cement mantle and at stem interfaces, and the number of the new cracks increased steadily with the loading cycles.

The effect of the debonded interface on cement stress and damage rate can further be evaluated from Table 2 and Table 3. Current results reveal that the cement stresses around proximal stem have significant variation than at distal end. The maximum tensile stress in the proximal cement mantle increases from 5.8 to 25.5 MPa when the gait loading comes to 8 million cycles. The variations in stress distribution at different loading stage are further demonstrated in Fig. 9. At debonded regions where critical damages occur, the cement stresses decrease to lower levels due to the reduction of load-carrying capability. Whereas at undamaged regions, particularly, the bonding boundary,

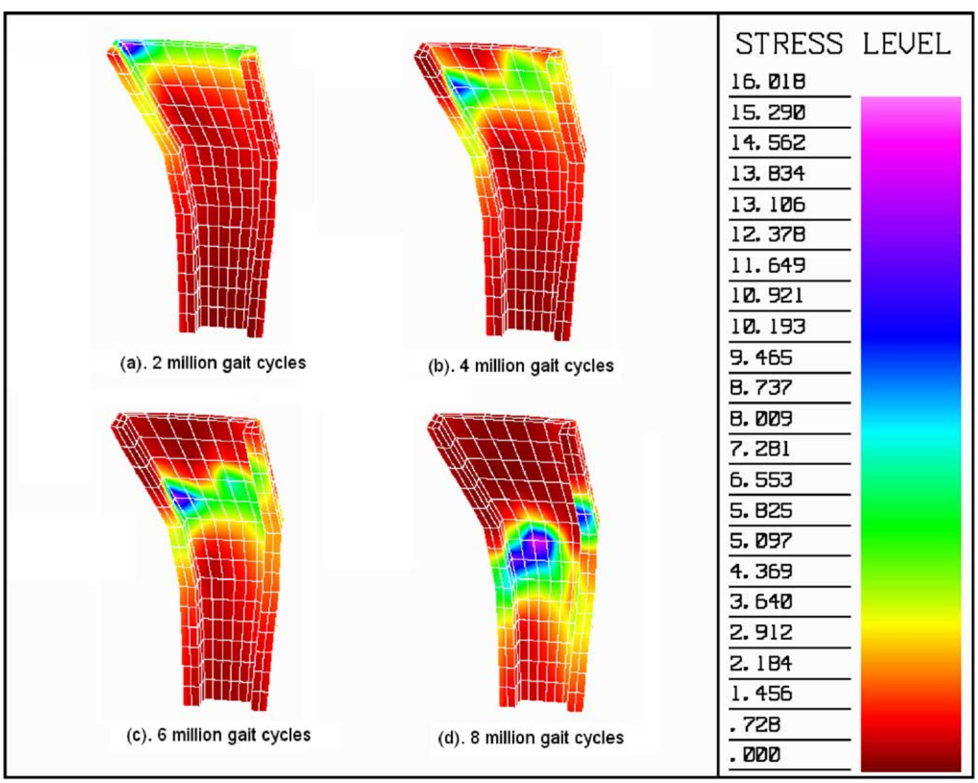

Fig. 9 Shaded image of von-Mises stresses induced in proximal cement after experiencing a certain number of loading cycles. The cement stresses were predicted at gait phase of 50%.

Table 3 Comparison of cement damage rate for femoral model with fully bonded interfaces and progressively debonded interfaces, respectively, which shows the effect of the interfacial debonding on cement damage rate

Gait cycles ($\times 10^6$)	Percentage of fatigue damage (%)	
	Estimated under progressively debonded interface	Estimated under fully bonded interface
2	1.9	4.6
4	3.7	5.5
6	9.6	6.2
8	19.9	6.7
10	25.5	7.4

there are remarkable increments. It seems that the high stressed area in cement mantle gradually transfers from damaged regions to undamaged regions, propagating with the progression of interface debonding. Owing to the increases of cement stress, the fatigue damage rate of cement mantle is raised to 25.5% after 10 millions loading cycles in follow-up. There are approximately 18% more of bone cement are damaged to failure when compared to that generated for model with a fully bonded interface (7.4%). At the same time, 8.3% of the bonding interfaces are destroyed and lose the load-carrying capability. The debonding rates of the cement—stem interface with the gait cycle are also shown in Fig. 8.

6. Discussions and lessons learned

The purpose of this paper is to propose a progressive failure analysis methodology to simulate the fatigue behaviors occurred in cemented hip prostheses. Three different interfacial bonding conditions, including firmly bonded, proximally separation and progressively debonded interfaces were assumed in the femoral model to validate the proposed simulation algorithm. The results of this study indicate that the development of the fatigue damage within the cement mantle is greatly affected by the interfacial bonding conditions.

Comparison of the results assessed for femoral model with firmly bonded and proximally separated interfaces shows that the accumulating behaviors of cement damages are similar but with different growth rates (refer to Figs. 5 and 7). Other numerical studies [8—10] also predicted similar findings even though different constructions of the femoral model were employed in analysis, particularly, in the modeling of the cement—stem interfaces. Since the load transferred from stem to cement occurs primarily across the interfaces, the deterioration of interface bonding will change the load-transferring path in cement mantle. Thus, modeling the interface accurately is essential in determining the cement stress under different loading periods.

As stated in previous sections, the Coulomb friction interface with various friction coefficients was employed by majority of researches to model the debonding status at cement—stem interface. As reported in [10], a reduction of friction coefficient induced higher cement stress and damage rate, which in turn resulted in a significant reduction of the fatigue life. This clearly shows the high sensitivity of fatigue damage to friction coefficients. The determination of friction coefficients is therefore of importance in predicting the damage behavior by this approach. However, this work is elaborative in experiments because the friction coefficient always varies with the surface characteristics of bonding materials [28,29], and the cement—stem interface behaves dissimilar characteristics with the progression of damaged interface during the long-term loadings [2]. Therefore, the use of Coulomb friction element with a single-valued material property [30] to characterize such adhesive interface is worth for further discussion. Besides, for most numerical investigations including the first two modes presented in this study, the interface bonding conditions assumed in femoral model were not changed with the development of damaged cement. In other words, previous investigations did not take account of the interfacial debonding effect on cement stress. However this effect actually brought the damage rate to different values and prompted a different pattern in damage accumulation process compared to that derived from fatigue experiments. This difference can be ascribed to that the debonding of the cement—stem interface occurring clinically was not properly replicated in numerical simulation.

On the other respect, reviewing the results obtained in different cement fatigue tests [25,26], we can conclude that the developing pattern of fatigue crack within cement mantle is similar to the failure phenomenon observed on the retrieval bone cement [2,4]. Cracks were observed to initiate at the pores along the cement—stem interfaces or stem corner at earlier loading stage and some of the cracks might propagate to final fracture in subsequent loading cycles. More new cracks were also initiated within the cement mantle due to the raise in cement stress caused by the interfacial debonding. Recent crack analysis on an idealized cemented stem [31] further demonstrated that cracks initiated within cement mantle and at stem surfaces grew quickly at initial and the total crack lengths also increased with the loading cycles. These phenomena not only describe the fracturing behavior of cement mantle, but also firmly verifies that the growth rate of cement damage is similar to that evaluated under the third mode presented in current study.

Based on these findings [25,26,31], the damage accumulation scenario of the bone cement can then be described as the mechanical failure in the form of the initiation of cracks and further growth in crack length with the loading cycles. In fatigue tests, the crack initiation is easier to monitor than crack growth. Consequently, the number of cracks initiated within the cement mantle and at the cement—stem interface is served as the main parameter to characterize the fatigue behavior of cemented hip prostheses under gait loadings. The failure scenario on crack initiation rather than crack growth within cement mantle thereby becomes the main concerns in this study. Since the cemented femoral model used in analysis was free of voids or defects, local fracture were assumed to originate within the cement mantle when the damage accumulation in principal directions reached the critical value. Besides, the evolution of the bonding conditions with loading duration was taken into consideration in simulation process to model the progressive deterioration of the cement bonding. As was predicted, the damaged regions gradually propagated from proximal anterior-medial regions toward the medial and postero-lateral regions along circumferential direction; whereas at the distal prosthesis tip, that propagated toward the proximal cement.

Referring to results available in literatures, the peak tensile stresses occurred at proximal cement for cemented femoral model with a fully bonded and debonded interface were 2.4 MPa and 4.9 MPa [6]; 1.4 MPa and 4.6 MPa [5], in which the debonded interface was modeled by Coulomb friction interface. Such variations of cement stress clearly showed the influence of the interfacial debonding in overall sense. However, as shown in Fig. 9, the debonding of the interface affects the stress level as well as its distribution within cement mantle. This influence has localized characteristics at critical regions rather than on entirety of cement mantle. For the femoral model experiencing 4 million loading cycles, the tensile stresses within the proximal cement change their magnitudes with variations ranging from −8.0% to 500% when compared with those generated for undamaged femoral model with a fully bonded interface. At this loading duration, the maximum tensile stress at critical regions has reached 12.0 MPa. This is greater than the fatigue strength of the bone cement and hence the fatigue failure is likely to initiate in these regions after certain number of loading cycles. Current results further indicate that with the increase of loading cycles the stress variations become more prominent, which enable the maximum cement stress to exceed the tensile strength. It is expected that higher cement stress may prompt the small cracks to propagate within the cement mantle.

Under this situation, the crack growth process will dominate subsequent fatigue behavior of cemented hip prostheses. Generally the prediction of crack growth is governed by the Paris and Erdogan [32], in which the effective stress intensity factor rather than the tensile stress at crack sites prevail the characteristics in crack propagation. Therefore, as a resistance to crack propagation, the fatigue threshold and fracture toughness of bone cement instead of the cyclic fatigue characteristics become the main properties affecting its fatigue life.

Although such crack propagation behavior was not investigated in this study because of the complication in crack simulation for three-dimensional femoral model without any embedded defects, comparisons between the results predicted by current simulation model and experimental observations have shown great consistence in crack initiation behavior of cement mantle. This confirms that the use of critical damage rate instead of the number of cracks to quantify the cement failure is reasonable. It is obvious that the simulation on fatigue behavior of cemented hip prostheses by numerical approach is feasible.

7. Conclusions and future plan

In this paper, a computer algorithm was proposed to simulate the fatigue behavior of cemented hip prostheses under physiological conditions. To be a pre-clinical validation of artificial hip implants with new designs, the simulation scheme should accurately mimic the fatigue behaviors in a more realistic way. In particular, the interfacial debonding effect on cement stress distributions and damage rates should be considered in fatigue simulation. For this reason, the progressively debonded interfaces instead of the Coulomb friction interfaces are employed to model the debonding of cement—stem interface.

Similar to the experimental investigations, the predicted accumulation damage rate of cement grows steadily with the gait cycles. For the development of the fatigue damage within cement mantle, current results have shown similar failure scenarios as those observed in clinical studies and fatigue tests. It is obvious that the proposed simulation algorithm yields realistic results and is clearly feasible in evaluating the long-term performance of cemented hip implants. Further work will investigate the propagation of the fatigue cracks initiating at pores within cement mantle by applying fracture mechanics. It is anticipated that this may help discriminating the substantial fracturing mechanism occurred in cemented prostheses and suggest the way to improve the fatigue resistance of bone cement in vivo circumstance.

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