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Gao, Y, Jin, Z, Wang, L et al. (1 more author) (2015) Finite element analysis of sliding distance and contact mechanics of hip implant under dynamic walking conditions. Proceedings of the Institution of Mechanical Engineers Part H - Journal of Engineering in Medicine, 229 (6). 469 - 474. ISSN 0954-4119

https://doi.org/10.1177/0954411915585380

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Finite element analysis of sliding distance and contact mechanics of hip implant under dynamic walking conditions

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Abstract: An explicit finite element method was developed to predict the dynamic behavior of the contact mechanics for a hip implant under normal walking conditions. Two key parameters of mesh sensitivity and time steps were examined to balance the accuracy and computational cost. Both of the maximum contact pressure and accumulated sliding distance showed good agreement with those in the previous studies using the implicit finite element analysis and analytical methods. Therefore, the explicit finite element method could be used to predict the contact pressure and accumulated sliding distance for an artificial hip joint simultaneously in dynamic manner.

Keywords: explicit finite element method, kinematics, contact mechanics, artificial hip joint, rotation vector

1. Introduction

Although metal-on-ultra-high molecular weight polyethylene(UHMWPE) hip implants have been widely used in orthopedics to treat severe hip joint diseases, aseptic loosening resulting from the UHMWPE wear debris is still a key factor limiting their longevity[1-3]. The contact mechanics, including contact pressure and sliding distance, are of great importance to the wear performance of the UHMWPE cup, and numerous studies on this issue have been carried out[4-6]. Implicit finite element(FE) method has been widely used to predict the contact pressure for artificial hip joints. Both Maxian[4] and Liu[6] used this method to calculate the contact pressure of the UHMWPE cup. Hua[7, 8] investigated the contact pressure using this method under different conditions such as edge loading and cup inclination. Bevill[9] also used the implicit FE method to calculate the contact pressure of a hip implant and retrieved the relative sliding distance on the cup surface from the FE result. However, most previous studies using the implicit FE method do not obtain sliding distance through the FE result, and the sliding distance is generally calculated using the Euler rotation method[10, 11]. Saikko and Calonius[10] developed this numerical method to estimate the slide track between the femoral head and the acetabular cup of an artificial hip joint, and later Kang[11] used similar method to predict the accumulated sliding distance on the cup.

Most of the previous studies have calculated the contact pressure and accumulated distance separately using different methods. Besides, the numerical method for accumulated sliding distance could only calculate the relative sliding distance of a point from its current position to a new position without considering whether contact occurs at this point. In fact, if no contact occurs at a point, the relative sliding distance is meaningless. Thus, it needs additional process to judge the contact situation of a node before calculating its relative sliding distance. In addition, there are instants when contact and relative motion occur simultaneously and under this condition, Euler rotation method is not applicable. On the other hand, an explicit FE method has been introduced since 1970s and used more recently to predict both the contact mechanics and the kinematics of artificial knee joints[12] simultaneously. However, to the best of authors' knowledge, there are still no reports that the explicit FE method has been used for artificial hip joints. Therefore, this study focused on the application of an alternative dynamic explicit finite element method to predict the contact pressure and accumulated sliding distance of an artificial hip joint simultaneously.

2. Materials and methods

2.1 Geometric modeling

An artificial hip joint was modeled in order to develop an explicit finite element method(FEM) to investigate its dynamic contact mechanics. Fig.1 (a) shows the geometries of this model. The key geometric parameters of this model, taken from Kang[11], are listed in Table 1. The cup was anatomically positioned at 45° inclination and fully constrained at its outer surface, and a fixed coordinate system(*x, y, z*) was placed at the center of the head(Fig.1(a), the positive x-axis was pointed medially, the positive y-axis was oriented posterior and perpendicular to the x-axis, the positive z-axis was pointed upwards). Only normal walking was considered in the simulation. Three-dimensional forces(three forces lie in the three axis of the fixed coordinated system) from Paul[13] were applied at the head center. The original movement waveforms including flexion-extension(FE), abduction-adduction(AA) as well as internal-external rotation(IER), taken from Johnston and Smidt[14], were transformed into incremental rotation vectors(in the section 2.2) and then applied at the center of the head. The orientations of both the forces and motions were adjusted according to the fixed coordinate system. The stem was given three initial angles(FE:-24.9°, AA: 1.5°, IER:0°) to correspond to the initial position of the walking gait.

2.2 Incremental rotation vector calculation

The original FE, AA and IER angles at a time instant were represented through the Euler rotation angles to enable the stem to rotate continuously from the beginning position to a new position. A moving coordinate system XYZ was fixed to and located at the centre of the femoral head. This moving coordinate system was rotated with the head during a gait cycle, and its initial orientation was in accordance with the fixed coordinate system in section 2.1. The Euler rotation started from the FE around the X-axis, and then followed by the AA and the IER about Y-axis and Z-axis of the moving coordinate system respectively[11]. Incremental rotation vectors were therefore calculated, according to the static movement waveforms. The movement waveforms in section 2.1 were divided into N instants. For arbitrary two adjacent instants i and $i+1$, both Euler rotation matrix R_i and R_{i+1} were calculated according to Saiko and Calonius[10], and then the incremental rotation vector between these two instants was obtained from the known R_i and R_{i+1}(Craig[15]). Then inverse Euler rotation R_i^{-1} was applied to both R_i and R_{i+1}, the incremental rotation vector between R_i and R_{i+1} was converted to a new incremental rotation vector corresponding to the fixed coordinate systems. In this way, all incremental rotation vectors corresponding to the fixed coordinate system(Fig. 1(a)) were calculated, which were used to represent the continuous rotation for the hip implant model in Abaqus[16].

Three different numbers of the discrete instants of 21, 41 and 81 were used to represent one gait cycle and check the accuracy of the predicted sliding distance and yet balance the computational time at the same time. The number of 41 discrete instants was found to be adequate, with an error of the predicted accumulated sliding distance less than 5%.

2.3 Finite element(FE) modeling

The conventional finite element software Abaqus version 6.12 was used; Abaqus/Explicit module was adopted to perform the FE analysis for the artificial hip joint model, specified in Section 2.1. As a comparison, Abaqus/Standard module was also used to perform the same FE analysis for this model. The Abaqus/Explicit module is based on the implementation of an explicit integration rule, which means the equations of motion for each body are integrated using an explicit central-difference integration rule and does not require iterations. However, the Abaqus/Standard module adopts an implicit integration rule, which means the operator matrix must be inverted and a set of simultaneous nonlinear dynamic equilibrium equations must be solved at each time increment, thus numerous iterations are needed for each time increment[17].

The FE model of the artificial hip joint is shown in Fig.1(b). The acetabular cup was UHMWPE, which was considered as a non-linear elastic-plastic material according to Fregly[18] and Kluess[19]. The head was cobalt-chromium-molybdenum (CoCrMo) and treaded as homogeneous and linear elastic. The material parameters are listed in Table 1. Both the cup and the head were meshed by 8-node structured hexahedron elements. The head was treated as a rigid body since its elasticity modulus was two orders of magnitude higher than that of the UHMWPE and meshed by an element size of 0.4 mm to accurately represent its geometry(about 217000 elements). The femoral stem was titanium alloy and meshed by 4-node tetrahedron elements(about 25000 elements) with a coarse element size of 2.5 mm. The contact pair between the cup inner and head outer surfaces was established, with a friction coefficient of 0.05[20]. Two key parameters of mesh sensitivity and time steps were examined for the explicit FE method. First, the mesh sensitivity of the cup was investigated with an element size of 2 mm, 1.5 mm and 1.25 mm respectively and 1.5 mm(about 4500 elements) was finally chosen(the differences of both the contact pressure and the sliding distance were less than 10%). Second, the time step for each interval in the simulation was carefully estimated to balance the model accuracy and the computational cost according to Abaqus Tutorials[21]. The walking process was considered slow enough (quasi-static) that it could be solved using the explicit solution method. For such a quasi-static process in explicit FE method, time intervals in a walking cycle and time steps with each interval(stable time increment) were important. Default time steps in Abaqus were chosen. Appropriate time intervals were chosen for a gait cycle. As mentioned in section 2.2, the whole walking gait cycle of 1 s was divided equally into 41 instants, to represent the time variation of both the load and the motion. From the consideration of the explicit FE analysis, the time interval was chosen to be about 10 times of the time period of the lowest vibration mode to ensure the accurate prediction[21]. The time period corresponding to the lowest vibration mode for the artificial hip joint model was 0.0023 s(corresponding frequency was 432 HZ). Therefore the time interval was chosen as 0.025 s, consistent with the 41 discretised instants in a gait cycle. Besides, the default damping coefficient of 0.06 was used to consider the damping associated with volumetric straining and to control high frequency oscillations[22]. As a comparison, the implicit FE method was also used to do the same FE analysis for the hip implant.

For the artificial hip joint model, the total computational time using the explicit FE method at a fixed cup element size of 1.5 mm was about 5 hours(on a 3.5GHz personal computer), and about 4 hours for the implicit FE method.

3. Results

The effects of different mesh sensitivity on the predicted accumulated sliding distance for the conventional model are shown in Fig.2. It is clear that the maximum accumulated sliding distance varied little with the element size and was consistent with the result of Kang et al.[11]. The difference of the predicted maximum contact pressure at any instants for different element sizes was less than 10%(the results are not shown). Therefore, the cup element size of 1.5 mm was deemed to be adequate. Fig.3 shows the contours of the accumulated sliding distance at different walking instants under a fixed element size of 1.5 mm for the artificial hip joint model. The accumulated sliding distance gradually increased and reached a maximum value of 20.31 mm at the node A(shown in Fig.3 & 4) which was close to the center of the cup inner surface at the end of the gait cycle.

Fig.4(a) and (b) show the comparison of the contact pressure at different walking instants under a fixed element size of 1.5 mm for the conventional cup between the implicit FE method and the explicit FE method. The distributions of the contact pressure at the same instant were similar and the difference of the maximum value at 65% gait cycle was less than 3%(13.04 MPa for the implicit FE method, 12.98 MPa for the explicit FE method). Fig.5 further reveals the distributions of the contact pressure at different walking instants between the two different solution modules.

4. Discussion

The aim of this study was to develop an explicit FE method to simultaneously predict contact pressure and accumulated sliding distance of an artificial hip joint. The predicted maximum sliding distance, based on the explicit finite element method, was in good agreement with the result using the numerical method by Kang et al.[11]. Although both the cup and head diameters in this study were the same as Kang et al.[11], the maximum value of the accumulated sliding distance was slightly different between the two studies. The maximum accumulated sliding distance of 20.31 mm(node A) using the explicit FE method was within the contact area at the end of a gait cycle, while the previous study by Kang et al. only considered the maximum accumulated sliding distance(23.38 mm) at the node B(shown in Fig.3& 4) which was almost out of the contact zone after 65% of a gait cycle.

Both three-dimensional forces and multidirectional motions were considered in this simulation to predict the contact pressure of an artificial hip joint using the explicit FE method. The contact pressure using the explicit method was of overall good agreement with that using implicit FE method. Therefore, the explicit FE method had the advantage to predict the contact mechanics and kinematics of artificial hip joints simultaneously. For a conventional artificial hip joint considered in the current study where there was only one pair of contact surfaces, the predictions of both the contact pressure and accumulated sliding distance agreed well with those using the implicit FE and analytical method.

Although the dynamic explicit FE method was applied for a conventional hip implant, it could be more effectively applied to other forms of hip implants where there are more than one contact pairs and the relative motions are not prescribed such as in a dual mobility hip implant. Such an implant has shown good stability and becomes widely used recently in clinics[23, 24]. Previous studies [25-27] on dual mobility hip implants have mainly focused on retrievals analyses and experiments for their wear and motion performance, and both inner and outer relative sliding motions have been found in these studies. Because the motion of dual mobility hip implants is not prescribed, the dynamic explicit FE method probably is the best way to investigate their kinematics as well as the contact mechanics.

Although the dynamic explicit FE method was shown to be able to accurately predict the kinematics and contact mechanics of hip implant, the current study has a few limitations. Only a fixed normal gait was considered and other gaits such as climbing stairs and sitting down will be investigated. Future studies will also focus on the application of the explicit method to the dual mobility hip implant and the experimental validation, particularly the relative motion at different contact surfaces .

5. Conclusions

A dynamic explicit finite element method was applied to predict the kinematics and contact mechanics of artificial hip joints. Comparison of contact pressure between this explicit method and implicit FE method was made for artificial hip joint. And comparison of accumulated sliding distance between this method and numerical method by Kang et al. was also made for artificial hip joint. The explicit finite element method was shown excellent ability to predict the kinematics and contact mechanics for artificial hip joint.

Acknowledgements

The work has been supported by both the State Key Laboratory for Manufacturing System Engineering and National Science and Technology Major Project of China and “the Fundamental Research Funds for Central Universities’’, the Program of the National Nature Science foundation of China [grants number 51205303], National Science and Technology Supporting Program [grants number 2012BAI18B00], National Science Foundation Project of China [grants number 51323007].

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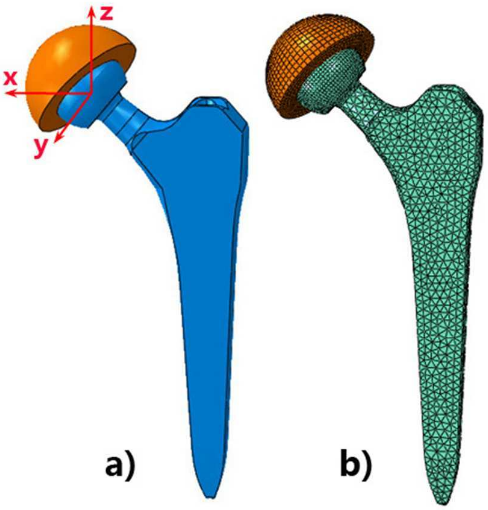

Fig.1 CAD (a) and FE models of conventional artificial hip joint (b)

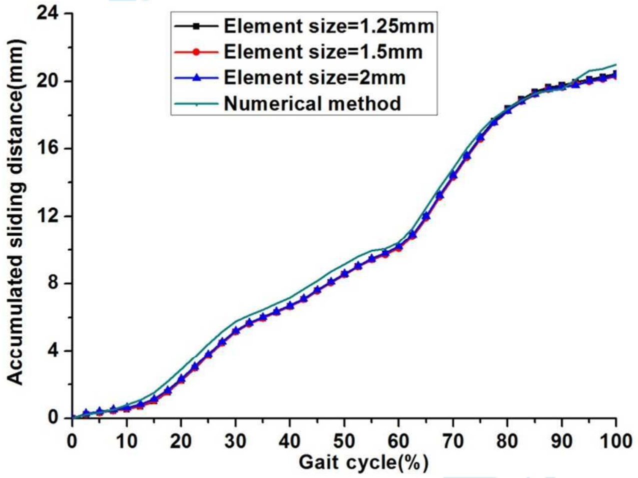

Fig.2 Effects of different element sizes on the maximum accumulated sliding distance of the cup as a function of the gait cycle for the conventional artificial hip model

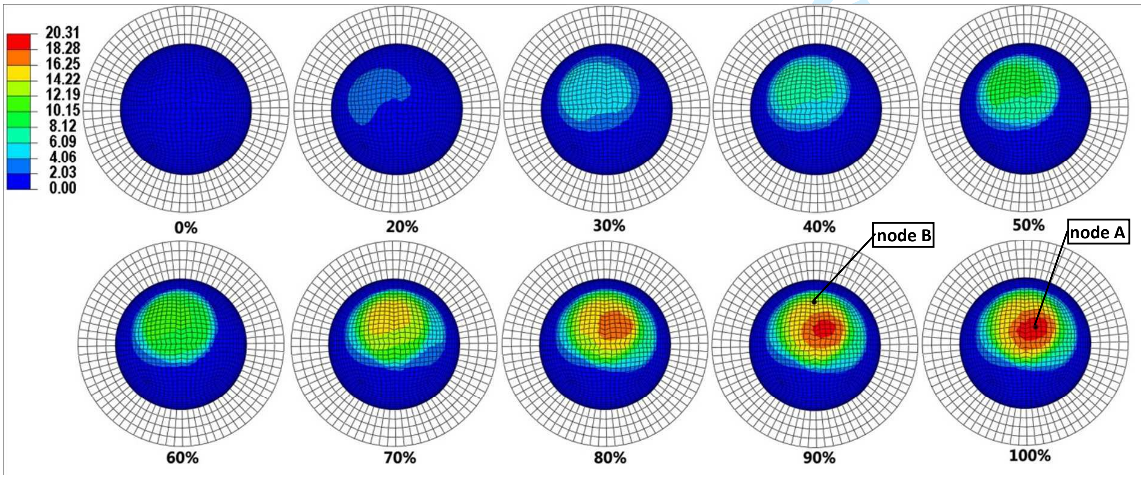

Fig.3 Contours of the cup inner accumulated sliding distance(mm) at different percentage of the gait cycle for the conventional artificial hip joint model predicted by the explicit FEM under a fixed element size of 1.5 mm

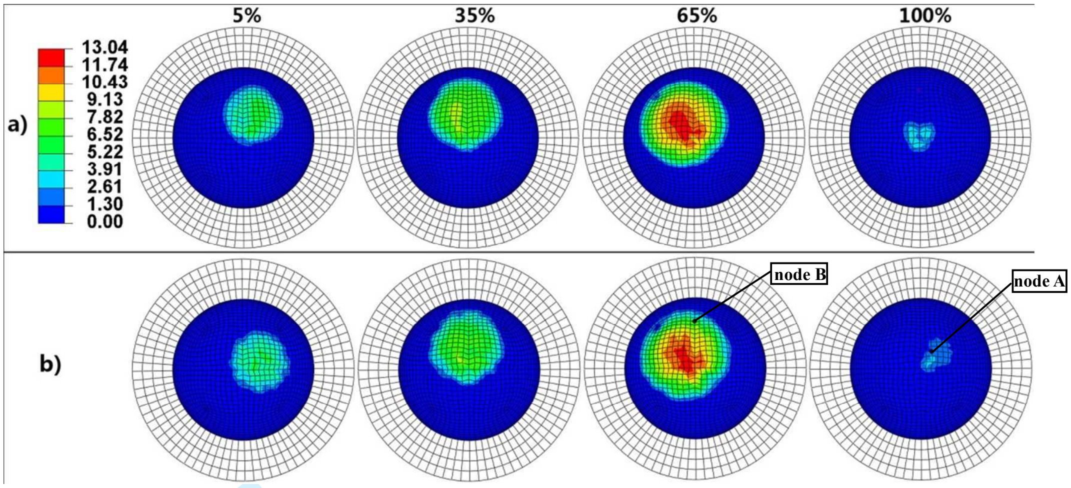

Fig.4 Comparison of the contours of the contact pressure(MPa) at different percentage of the gait cycle for the conventional artificial hip joint model between implicit FE method (a) and explicit FE method (b)

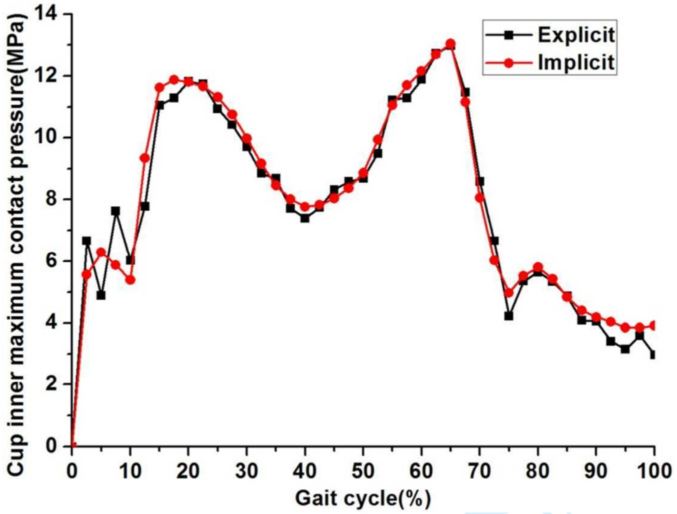

Fig.5 Comparison of the maximum contact pressure as a function of the gait cycle for different finite element analysis methods for the conventional artificial hip joint model

Table 1 CAD and FE model key parameters of conventional artificial hip joint model

	Inner radius(mm)	**Outer radius(mm)**	**Materials**	**Density (g/mm$^{3)}$**	**Elastic modulus (GPa)**	**Poisson's ratio**	**Yield** strength(MPa)
Head	\	14.0	CoCrMo	7.61	217	0.30	\
Cup	14.1	22.1	UHMWPE	9.32e-1	1	0.45	23.56