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Contributions of Non-Spherical Hip Joint Cartilage Surface to Hip Joint Contact Stress

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***Abstract*—The natural non-spherical incongruent hip joint cartilage surface is normally assumed as spherical in shape, which has been extensively applied in orthopedic clinic, hip joint simulation studies and hip joint prosthesis design. The aim of the study was to investigate the contributions of non-spherical incongruent hip joint cartilage surface to the hip joint contact stress, and to assess the effect of simplified spherical assumption on the predicted contact stress.**

Based on our previous anatomic studies that the acetabular cartilage surface was demonstrated as rotational ellipsoid in shape, three finite element (FE) models involving the natural hip joint cartilage shape, the hip joint cartilage shape replaced by the rotational ellipsoid and the sphere, respectively, were developed using the computed tomography (CT) image data of healthy volunteers. The FE predictions of contact stress on the replaced hip joint cartilage surface were compared with that on the natural hip joint cartilage surface.

The result showed that the non-spherical hip joint cartilage surface contributed to the optimal contact stress magnitude and distribution. The replaced fitting spherical surface led to the increased contact stress of hip joint and the uneven distributed patterns of contact stress, whereas the replaced fitting rotational ellipsoid surface was comparatively more consistent with the natural results than the sphere one. The surface fitting error of the replaced rotational ellipsoid was fewer than that of the replaced sphere. These results indicate that the simplified spherical assumption will lead to misestimating the contact mechanics of hip joint, and the rotational ellipsoid model rather than the sphere model may represent the hip joint contact surface applied in the hip joint simulation study and the hip joint prosthesis design.

I. . INTRODUCTION

THE natural hip joint cartilage surface, both the acetabulum and the femur head, is not simply spherical where the acetabulum is even less spherical than the femoral head[1-3]. This anatomic morphological feature plays an important role in the hip joint biomechanics, documented as follows: 1)it contributes to the relatively low and more homogeneously distributed hip joint contact stress [4]; 2) the degree of hip joint incongruity, which the acetabulum is less spherical than the femur head, is essential for normal synovial joint lubrication and load support function, as well as nutrient and waste product transport to and from the cartilage [5-6]; 3) the impact of cartilage surface shape on articular cartilage biomechanics is essential for cartilage development and longevity, which stimulates the mechanical signals for modifying cellular behavior and tissue metabolism [7].

Although the hip joint cartilage surface is non-spherical in shape, the precise geometric representation of hip joint cartilage surface is not well documented. Furthermore, the implication about the effect of non-spherical hip joint cartilage surface on the contact mechanics of hip joint remains unclear. As a result, the hip joint cartilage surface is still assumed as a spherical shape in clinical practice, and the sphere model representing the hip joint cartilage surface has been widely used in the computer simulation analysis of the hip joint biomechanics and the design of the hip joint prosthesis [8, 9]. Recently, several studies report that the calculated hip contact force is sensitive to the hip joint geometry [10]. In particular, the simplification to the cartilage surface of hip joint has a dramatic effect on the predicted magnitude and distribution of hip joint contact stress in the hip joint simulation analysis [11]. Combined with reverse engineering technique, surface-fitting algorithms and mathematical curve surface theory, our previous study found that the shape of the acetabular cartilage surface was not spherical but rotational ellipsoidal [12].

Based on the previous study, the aim of this study was to: 1) elucidate the contributions of non-spherical hip joint cartilage surface to hip joint contact stress; 2) assess the effect of hip joint spherical surface assumption on the predicated hip joint contact stress; 3) evaluate a new geometric model representing the hip joint spherical surface for the improvement of simulation precision.

II. MATERIALS AND METHODS

A. Finite element model generation

Two three-dimensional(3D) finite-element (FE) models of the natural hip joint were generated based on the CT images of one male and one female healthy volunteer(male: 75kg in weight and175cm in height; female: 60kg in weight and 163cm in height). In order to analyze the effects of hip joint cartilage surface on the hip joint contact stress, both of the acetabular cartilage surface and the femur head cartilage surface were replaced by a fitting sphere and a fitting rotational ellipsoid, respectively. Based on our previous study, the rotational ellipsoid was shown as a better-fit mathematic representation of the acetabular cartilage surface. Since the

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femur head has been reported as non-spherical in shape, we hypothesize that the femur head can be replaced by a fitting rotational ellipsoid.

To generate the fitting sphere and the fitting rotational ellipsoid for hip joint cartilage surface, respectively, the surface-fitting error d was introduced to calculate the deviation distance between the mathematical curved surface and the natural surface, which is defined as follows:

$$d = \frac{1}{n}\sum_{i=1}^{n} \left| d_{pi} - d_{qi} \right| \qquad (1)$$

Where d_{pi} and d_{qi} are the three-dimensional coordinates of the mathematical curved surface and the natural surface nodes, respectively, and n is the total number of surface nodes [12].

To determine the hip joint cartilage surface node, the 3D geometric solid models of the acetabulum and the femur head were transferred to the triangulated mesh models. The triangulated mesh surface for hip joint cartilage surface was discretized into the surface point dataset (Fig.1). Using the optimal surface-fitting algorithms, the best-fitting sphere model and rotational ellipsoid model for hip joint cartilage surface were constructed (Fig.2). The optimal objective function was given by the minimal of the surface-fitting error d.

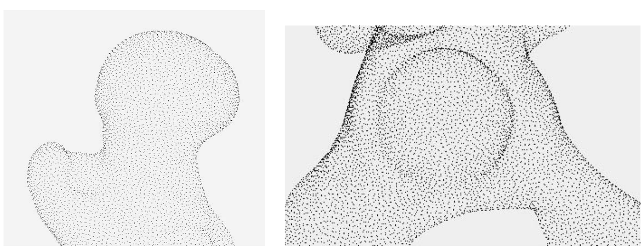

Fig.1.The surface point dataset of femur head （left） and acetabulum (right) based on the hip joint solid model.

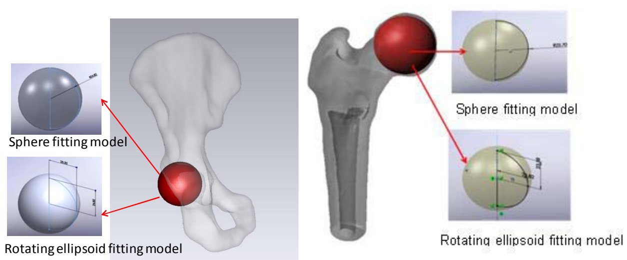

Fig.2. Sphere fitting model and rotational ellipsoid fitting model replaced the acetabular cartilage surface and the femur head cartilage surface, respectively.

B. Loading, boundary conditions and material properties:

Referenced by the published data in vivo hip loads study [13], the imposed loading conditions simulated the one-legged stance phase of a walking cycle. An external load equal to 5/6 body weight (BW) was applied in the vertical direction to the nodes constrained on the pelvis [14]. The nodes situated in the both areas of the sacro-iliac joint and the pubic symphysis were kept fixed in the x, y directions to simulate sacral and pubic support of the pelvic bone. The distal region of the femur in all degrees of freedom was constrained (Fig.3).

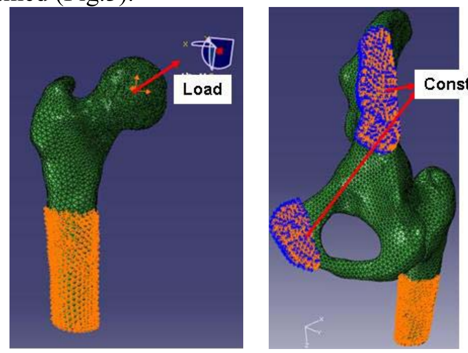

Fig.3. Loading and boundary condition assumed for the hip joint finite model.

The cortical bone and trabecular bone were represented as homogenous and isotropic with elastic modulus E=17GPa, and Poission's ratio v=0.3 for cortical bone, and elastic modulus E= 0.8GPa and Poisson's ratio v=0.2 for trabecular bone. The cartilages surface of femur head and acetabulum were assigned with a constant thickness of 1.28mm, and modeled as an isotropic, linear elastic material with E=10.4MPa and Poisson's ratio v=0.2[15]. A surface-based, finite sliding contact was defined between the femur head cartilage surface as master surface, and the acetabular cartilage surface as slave surface, with an assumed friction coefficient of 0.2. The commercial finite element software ABAQUS 6.6 was applied to analyze the contact stress of hip joint.

B. Data analysis

The fitting errors for these two kinds of parametric models were calculated, and the parameters of best-fitting spherical and rotational ellipsoidal models for subject-specific hip joint cartilage surface were tabulated. Predictions of peak contact stress and distribution pattern of contact stress for each replaced surface model were compared directly with the subject-specific FE model.

III. Results

A. Fitting errors and parameters of the best-fitting surface models

In generating the surface fitting model for the acetabular cartilage surface, the average fitting errors of the sphere model were 0.434 mm in male and 0.656 mm in female, respectively, while the fitting errors of the rotational ellipsoid model were 0.398 mm in male and 0.590 mm in female, respectively. Meanwhile, for the femur head cartilage surface, the average fitting errors of the sphere model were 0.374 mm in male and 0.404 mm in female, respectively, while the fitting errors of the rotational ellipsoid model were 0.348 mm in male and 0.373 mm in female, respectively. Overall, while generating the surface model for hip joint cartilage surface, the surface-fitting error of the rotational ellipsoid model was fewer than that of the sphere model both in male and female.

The parameters of the best-fitting sphere model and the rotational ellipsoid model for hip joint cartilage surface were calculated (table 1). For both male and female, the parameters of the rotational ellipsoid model showed that the flattening of ellipsoid for the femur head and the acetabulum approximate to 0.01 and 0.02, respectively, namely the cartilage surface of the acetabulum was relatively flatter than that of the femur head while femur head was optimal to the shape of sphere.

Tab.1. Parameters of the best-fitting sphere model and rotational ellipsoid model for hip joint cartilage surface (Unit: cm)

Hip joint cartilage surface	sphere model	rotational ellipsoid model	
	radius	Semi-major axis	Semi-short axis
Femur head	male : 23.70	23.82	23.58
	female : 21.23	21.39	21.12
acetabulum	male : 24.80	24.82	24.32
	female : 22.30	22.36	21.91

B. The contact stress in different models

The hip joint contact stress represented by von Mises stresses in the healthy natural hip joint model was more even over the cartilage surface. The peak stress on acetabular cartilage surface was 10.77MPa in male and 14.79MPa in female, respectively, while the peak stress on femur head was 11.19MPa in male and 12.22MPa in female, respectively (Fig.3).

Compared with the natural morphology of hip joint cartilage surface, the magnitude and distribution of contact stress for the two replaced surface models changed, but the degree of change varied. For both male and female, the peak stress predicted by the replaced fitting sphere model was higher than that by the replaced fitting rotational ellipsoid model (Fig.3). For the replaced fitting sphere model, stress concentrations were obviously shown in the anterior superior area of the acebulum and the upper area of the femur head, as well as in the whole rim of contact surface between femur head and acetabulum (Fig.4-5).

When compared with the replaced fitting sphere model, the degree and the area of contact stress concentration were substantially reduced for the replaced fitting rotational ellipsoid mode, which was showed in the posterior rim of contact surface between femur head and acetabulum (Fig.4-5). In terms of the magnitude and distribution, the predicted stress by the fitting rotational ellipsoid surface model was comparatively more consistent with the natural subject-specific model than the fitting sphere model (Fig.4-5).

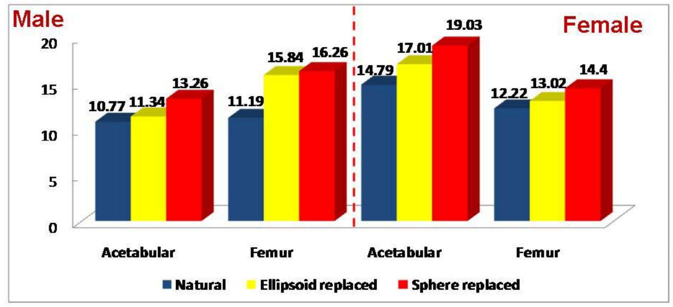

Fig.3.The contrast of contact stress on hip joint cartilage surface among the subject-specific hip joint, the hip joint surfaces (femur head and acetabulum) were replaced by sphere and the rotational ellipsoid, respectively.

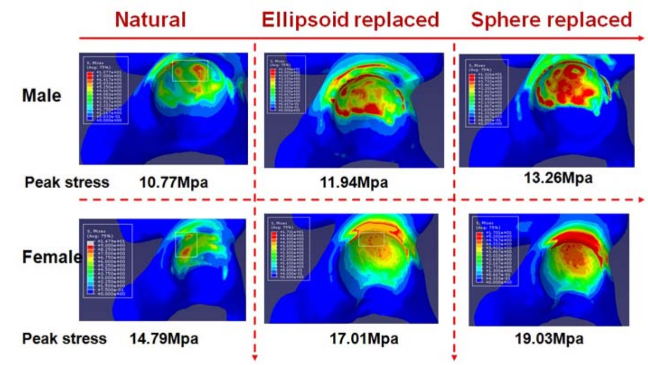

Fig.4.The comparison of contact stress distribution of acetabulum in male and female when the hip joint cartilage surfaces (femur head and acetabulum) were replaced by the sphere and the rotational ellipsoid, respectively.

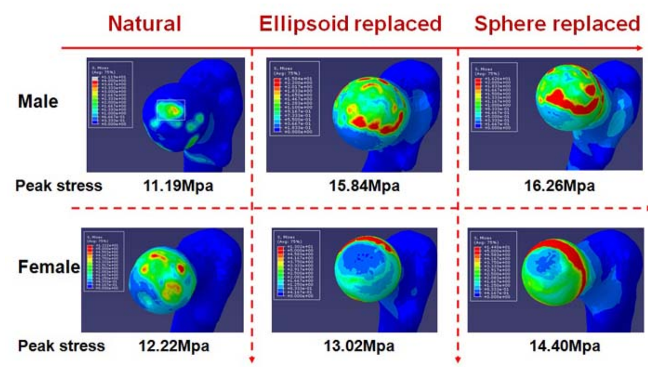

Fig.5.The comparison of contact stress distribution of femur head in male and female when the hip joint cartilage surface was replaced by the sphere and by the rotating ellipsoid, respectively.

IV. DISCUSSION AND CONCLUSION

The hip joint cartilage surface is normally simplified as sphere in shape in clinical practice, and the fitting sphere model representing the hip joint cartilage surface has been widely applied in the hip joint simulation study and the hip joint prosthesis design. For the purpose of improving the precision of current hip joint simulation study and providing a valuable reference for the hip joint prosthesis design, the present study investigates the contributions of non-spherical hip joint cartilage surface to hip joint contact stress, as well as evaluates the effect of hip joint spherical surface assumption on the predicated hip joint contact stress. The result of the present study showed that, though the average fitting error of sphere surface was about 0.5mm, the replaced fitting spherical surface led to the increased contact stress of hip joint and uneven distributed patterns of contact stress. In contrast, the non-spherical hip joint cartilage shape contributed to the optimal contact stress magnitude and more evenly distributed contact pattern.

Compared with the sphere surface, the average fitting error of the rotational ellipsoid surface was smaller and the predicted contact stress and contact distribution by the fitting rotational ellipsoid model were more consistent with the result of the natural non-spherical subject-specific model. These results indicate that the rotational ellipsoid model rather than the sphere model may be appropriate for representing the hip joint contact surface applied in the hip joint simulation study and the hip joint prosthesis design.

The contact stress predicted by the natural subject-specific hip joint model corresponded well to the previous simulation study [16-17]. The limitation of the study includes the simplified assumption of the cartilage as a homogenous, linear elastic material with the constant thickness which may lead to the overestimation of the cartilage stress. However, we focus only on the comparison of hip joint contact stress with varied cartilage surface shape, and all the calculated contact stress were analyzed under the some simulation conditions. CT images of only one male and one female health volunteer were applied in the study and the result may vary for individual anatomic morphology. Thus, it would improve the interpretability of the results by analyzing more hip joint models.

In conclusion, the non-spherical hip joint cartilage surface contributes to the relatively low and more homogeneously distributed hip joint contact stress. The simplified sphere assumption deviated from the anatomic morphology of hip joint cartilage surface change the contact mechanics of hip joint. The rotational ellipsoid surface rather than the sphere surface may represent the hip joint cartilage surface applied in the hip joint simulation study and hip joint prosthesis design.

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