Biomechanical Evaluation for Fibular Allograft Combined with Impaction Bone Grafting in Treating the Femoral Head Necrosis: Thorough Debridement or not?

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Abstract - Fibular allograft combined with impaction bone grafting is an effective hip preserving method that be employed for avoiding the total hip replacement in the early stage of the femoral head necrosis. However, whether thorough debridement should be used with FAIBG is controversial. Thorough debridement can better protect the anterolateral column and reduces the necrosis area of stress concentration phenomenon compared to partial debridement theoretically, but it will bring bigger trauma region and higher incidence of complications, and require longer surgery recovery time. In most cases, the choice is made based on the experience and preference of different surgeons. This study first proposes employing computational biomechanical technology to explore the different mechanical performance of FAIBG with or without thorough debridement, which provides biomechanical basis for choosing the proper treatment in clinic.

Keywords: Computational biomechanics, thorough debridement, fibular allograft combined with impaction bone grafting, anterolateral, stress transfer path

1 Introduction

There is a rapid increase in the incidence of the femoral head necrosis (FHN) all over the world, which is caused by the widespread of steroid [1,2] and alcohol [3-6]. FHN is associated with high morbidity and disability. Patients with FHN often have high risk to have collapse of femoral head, arthritis or dearticulation, and finally result in hip replacement (HR). The normal lifespan of a hip implant is about 12 years, so for the young age of the patients with HR, it is going to be several surgical treatments [7]. Hence, femoral head preserving is a better alternative treatment for patients with FHN in the early stage.

Fibular allograft combined with impaction bone grafting (FAIBG) is an effective head preserving method for avoiding total hip replacement (THR) in the early stage of FHN. FAIBG provides both repaired materials and biomechanical structural support during the healing of the necrosis region [8-11]. However, whether thorough debridement should be used with FAIBG is controversial. “With thorough debridement” means that the necrotic bone should be clean up completely; while “Without thorough debridement” means that the necrotic bone should be partial debridement. Thorough debridement can better protect the anterolateral column and reduces the necrosis area of stress concentration phenomenon compared to partial debridement theoretically, but it will bring bigger trauma region and higher incidence of complications, and require longer surgery recovery time. In most cases, the choice is based on the experience and preference of different surgeons. At the same time, the studies about comparing the risk of collapse of postoperative femoral head accompanied with thorough debridement and without thorough debridement are relatively rare.

To provide scientific biomechanical basis for FAIBG, this study presents two subject-specific FHN cases without collapse of the femoral head to compare the mechanical performance between FAIBG with thorough debridement and without thorough debridement.
2 Materials and Methods.

2.1 JIC classification

In 2001, the Japanese Investigation Committee (JIC) [12] revised diagnostic criteria to clarify the definition of osteonecrosis of the femoral head (ONFH). According to the JIC classification criteria, FHN are classified into subtypes A, B, C1 and C2, based on the location of the lesion in the weight-bearing area. Type A lesions occupy the medial one-third or less of the weight-bearing portion. Type B lesions occupy the medial two-thirds or less of the weight-bearing portion. Type C1 lesions occupy more than the medial two-thirds of the weight-bearing portion but don’t extend laterally to the acetabular edge. Type C2 lesions occupy more than the medial two-thirds of the weight-bearing portion and extend laterally to the acetabular edge.

Recent studies have shown that patients who conform to the JIC C criteria are suitable for FAIBG. But these conclusions are mainly based on clinical observation experience and require to be proved in both theory and practice. Whether employing thorough debridement with FAIBG or not is still controversial. Hence, we reconstructed two subject-specific models (including JIC C1 and C2, Figure 1) to provide biomechanical basis for FAIBG to explore the performance of different debridement region in treating FHN.

2.2 Generation of intact finite element models

A patient (P1) with weight of 70 kg who was diagnosed with JIC C1 FHN and a patient (P2) with weight of 60 kg who was diagnosed with JIC C2 FHN were selected for biomechanical evaluation on the proximal femur. Computed tomography datasets (0.5 mm thickness; Toshiba aquilion 64, Japan) of each case were employed to reconstruct solid models with grey level processing of the software MIMICS 15.1 based on the function of ‘Thresholding’, ‘Edit Masks’, and ‘Calculate 3D’. The solid models in the format of STL were input to 3-matic pre-processor, in which the surface-fitting could be performed. Based on the function of ‘Wrap’, ‘Patching’, we could find the fit hip to generate NURBS models. The interface between the ilium and femoral head was used to identify cartilage geometry. All NURBS models in the format of igs were input to ABAQUS V6.13 (SIMULIA co., France) to generate nonlinear elastic finite element models. Based on the initial hip geometry, we simulated the physiological and pathological models by different materials.

Then, all these models were input to ABAQUS V6.13 to generate isotropic 10-node tetrahedral elements. The mesh size was 4 mm. The initial models were consisted of elements (146879 of P1; 156471 of P2) and nodes (213970 of P1; 230541 of P2). In these models, single-legged stance was considered as a representative body position and a ground reaction force equivalent to body weight was performed on a rigid plate that was tied to the distal part of the femur in Figure 2. Constraints were applied on public symphysis and sacroiliac joint. All the six degrees of freedom were constrained to zero. Seven muscles were modeled as axial connectors, muscle forces were set according to the literature [13]: the adductor longus = 560 N, adductor magnus = 600 N, glutaeus maximus = 550 N, glutaeus medius = 700 N, glutaeus minimus = 300 N, piriformis = 500N and tensor fascia latae = 300 N. The models consist of cortical, trabeculae, cartilage and lesion bone. The material properties used in biomechanical experiment were obtained from the literature [14-16]: $E_{\text{cortical}} = 15100$ MPa, $E_{\text{trabeculae}} = 445$ MPa, $E_{\text{cartilage}} = 10.5$ MPa, $E_{\text{lesion}} = 124.6$ MPa, $\nu_{\text{cortical}} = 0.3$, $\nu_{\text{trabecular}} = 0.32$, $\nu_{\text{cartilage}} = 0.45$ and $\nu_{\text{lesion}} = 0.152$.

![Figure 1 3D subtype models of JIC Classification](image1)

![Figure 2 Load and constraint conditions](image2)
schematically in Figure 3. We assumed the anterolateral cortical stress corresponding to the debridement extent of necrotic lesion had an increased radius R (R=1/4r, 3/8r, 1/2r, 5/8r, 3/4r, 7/8r and r), where R=1/4r referred to the least debridement and R= r denote the thorough debridement. For the simulation of the allogeneic fibular implant, dimensions (80 mm in length and 6 mm in radius) were obtained from the manufacturer. The axial direction of fibula was defined by entry point and the lesion centroid. The entry point was located in the trochanteric lateral cortex of the femur. The distance of the cortical bone from the apex of the fibula was 5 mm. The rest of voids were occupied by impaction cancellous bone after debridement.

Figure 4 the principal stress distributions in the femoral head

3 Results

3.1 Stress transfer path

The principal stress transfer characteristics are the most important biomechanical index in evaluation of performance of FHN. In all femoral heads, the principal stress transfer patterns are computed when a mid-stance of gait occurs. Figure 4A and 4C show that the principal stress distributions in the healthy conditions are from the top of the femoral head to the femoral calcar. In Figure 4B and 4D, the stress transfer paths are broken off and the areas bearing principal stress are less than approximately 50% of the healthy simulations. The principal stress transfer efficiency reduces obviously.

3.2 Stress distribution of anterolateral column

FAIBG has a considerably small risk of structure collapse compared with untreated situation. Figure 5A and 6A show the healthy stress distribution of anterolateral cortical bone and the maximum stress value are 23.95 MPa of P1 and 25.99 MPa of P2. Figure 5B shows that JIC C1 stress of 30.31 MPa raises about 26.56%, which is higher than the healthy condition (P1). Figure 6B shows that the JIC C2 stress of 34.58 MPa raises about 33.05%, which is higher than the healthy condition (P2). Figure 5C and 6C show that the postoperative stress is 23.52 MPa in P1 and 25.31 MPa in P2, which is approximately 22.4% lower than the JIC C1 condition (P1) and 26.81% lower than the JIC C2 condition (P2) after FAIBG procedure. The peak stresses of the two postoperative cases return to near-healthy levels. It is obviously that the stress concentration regions in JIC C1 and C2 are the areas that the red arrows point to. After FAIBG procedure, the stress concentration regions are disappeared. Figure 5D-I and 6D-I show that stress has no significant changes as the debridement radius increasing.

3.3 The peak stress of the residual necrotic bone

Figure 7 displays that the debridement size will affect the stress gradient in the residual necrotic bone. Seven different necrotic debridement sizes, ranging from 1/4r to r, are chosen to study the effect of debridement radius on the residual necrotic bone. The relation between debridement size and the stress of the residual necrotic bone is shown in Figure 7. When the debridement radius is 1/4r, there is a 3762% increase in the peak stress compared to JIC C1 condition and a 1217% increase in the peak stress compared to JIC C2 condition. When the debridement is not less than 3/8r, the
peak stress in the residual lesion is rapidly falling and returns to the physiological level.

3.4 Model validation

The principle compressive trabecula loads principle compressive stress of the femoral head (Figure 8C/D), which correlates well with the bone density distribution (Figure 8B) [17]. The shape and location of the biomechanical transfer path for both load cases are consistent with the trabecular features in the cross-sections of the cadaver bone (Figure 8A) [18, 19]. It is clearly that trabeculae in the corresponding areas are thinner. In the same time, there are strong similarities of stress patterns between the simulation results of our study and the previous studies results in the literature [13]. Hence, we think that the FE results could mirror the physical phenomenon of the hip and evaluate the results.

Figure 8 Photograph (A), radiograph (B), the previous simulation results (C) and the computational results (D) of our study. The shape and location of the biomechanical transfer path (D) are consistent with the trabecular features in the cross-sections of the cadaver bone (A), BMD distribution (B) in radiograph and stress distribution in the previous simulation results.

4 Discussion

FAIBG represents a proven technique for maintaining the shape of the femoral head and reducing the risk of collapse of FHN in its early stages. Rosenwasser [20] first described, thorough debridement and bone grafting for treating FHN in 1994. This technique is an effective method for young patients with FHN in early stage, which will delay the progression of osteoarthrosis and subsequent THA. Tao W [21] reported a 80% clinical success rate with a mean follow-up time of 24 months among fifteen patients who had surgical therapy by thorough debridement with bone grafting. However, these procedures may cause serious artificial damage and complication by capsulotomies or the destruction of the cortical bone of the femur neck fundus, and require relatively high surgical devices and technique. In 2008, Shi FL [22] reported of 67 hips, with the treatment of internal bracket implanting with partial debridement for FHN. They came up with a 64.2% (43/67) success rate with an average
follow-up of 23 months. In 2013, Shi FL \cite{21} comments their results by treating 25 of 40 patients using allograft fibula with partial debridement for FHN. They reported the satisfactory results in 18/25 (72%) patients with 24 months follow-up. These minimally invasive procedures could reduce the artificial damage and complication but got a poorer clinical outcome, since these procedures couldn’t provide both repaired materials and biomechanical structural support during the healing of the necrosis region. FAIBG with proper debridement is an effective head preserving method and we have achieved an average clinical success rate of 90.3 % with a mean follow up time of 37.5 months \cite{24}. All these views are based on the clinical observation experience and lack of biomechanical basis. Hence, both “thorough debridement” and “partial debridement” are not accepted universally because these is no compelling evidence indicate that which method could be better in reducing the collapse risk of femoral head. It encourages us to introduce our experiences on computational biomechanical analysis of debridement extent to reduce collapse risk of FHN.

In our study, we adopted a subject-specific computational approach to consider changes in stress distribution of anterolateral cortical bone and the residual necrotic bone. Figure 4 shows that the stress transfer path in both JIC C1 and C2 are completely broken off, which indicate that surgical intervention should be involved. The effect of debridement size with FAIBG on the collapse risk is clearly demonstrated in Figure 5-6. After FAIBG, the stress of anterolateral cortical bone in all conditions could return to physiological level and the decrement/increment of stress almost less than 0.1 percent as the debridement radius increasing in two cases; hence, the collapse risk of femoral head can be reduced effectively using allo-fibula support to bear the load. When debridement size is not less than 3/8r, the von Mises stress of the residual bone also return to pathological level, which denotes that the progression of necrosis wouldn’t deteriorate after surgical intervention. Our results provide specific biomechanical evidence to support the viewpoints that FAIBG can resist the collapse of FHN and FAIBG with thorough debridement has lower risk for developing collapse risk compared to partial debridement.

5 Conclusions

In this paper, we propose employing computational biomechanical technology to explore the different mechanical performance of FAIBG with or without thorough debridement, which provides biomechanical basis for choosing the proper treatment in clinic. Eighteen computational models were constructed and used to simulate two subtypes of FHN with seven debridement radius of FAIBG procedure. The simulation results provide specific biomechanical evidence to support that FAIBG procedure can resist the collapse of FHN. Furthermore, FAIBG without thorough debridement, which not only requires relatively low surgical devices but also reduces artificial damage, seems to be a better method in resisting the collapse of JIC C1 and JIC C2 FHN. This paper is a preliminary approach to investigate FAIBG procedure with thorough debridement, more detailed analysis will be reported in the near future.

6 Declaration of conflicting interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

7 Funding

This study is supported by National Science Foundation of China under Grant (81173284) and Joint Guangdong Science and Technology Department and Guangdong Traditional Chinese Medicine Academy Research and Speciality Fund (2012A032500005) and Natural Science Foundation of Guangdong Province (S2013010011992, S2012010008123). There are no financial and personal relationships with other people or organizations that could inappropriately influence our work for all authors of this paper.

8 Acknowledgments

The authors would like to thank Ms. Yang Xiaolu and Mr.Song Junjun for data analysis support.

9 References


