Research Report

Journal of
INTERNATIONAL
MEDICAL RESEARCH

Journal of International Medical Research
2018, Vol. 46(2) 693–698

DOI: 10.1177/0300060517719625
journals.sagepub.com/home/imr
SAGE

Analysis of damage in relation to different classifications of pre-collapse osteonecrosis of the femoral head

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Abstract

Objective: This study aimed to investigate the damage pattern of the stress transfer path (STP) for the Japanese Investigation Committee (JIC) classification of pre-collapse osteonecrosis of the femoral head. We aimed to provide a specific biomechanical basis for treatment decisions of each subtype.
Methods: Five computational models were used in the experiment. Different necrotic classifications were simulated based on the JIC classification system. Damage patterns of the STP were used for qualitative assessment and average stresses were used for quantitative analysis.
Results: The STP of type A showed a strong similarity to the healthy level, which was consistent with the bone density distribution in X-rays and previous simulations results. The damaged area of principal stress of type B was approximately 25% of the healthy level. The STPs of types C1 and C2 were broken and the damaged areas of principal stress were more than 50% of the healthy level. The efficiency of stress transfer was reduced.
Conclusions: These results indicate that the damage patterns and stress transfer efficiency of the femoral head are associated with necrotic classifications.

Keywords

Computational biomechanics, damage pattern, osteonecrosis of the femoral head (ONFH), stress transfer path, JIC classification, hip-preserving therapy

Date received: 13 February 2017; accepted: 12 June 2017

Introduction

Osteonecrosis of the femoral head (ONFH) is considered as a common debilitating and progressive disease in the orthopaedic field, usually in patients aged between

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20 and 50 years (average, 36 years). Management of ONFH is still a challenging task. Clinical doctors and researchers share a common goal of choosing a safe and effective treatment procedure for protecting the femoral head of patients with ONFH. Several hip-preserving procedures have been developed to maintain or reconstruct the mechanical environment and interrupt the disease path of articular collapse. These procedures include core decompression, transtrochanteric rotational osteotomy, free and non-vascularized fibular grafting, and fibular allografts. Total hip arthroplasty (THA) is considered as the standard and effective treatment option for patients with femoral head collapse in terms of pain relief and functional improvement. However, many authors have reported high rates of failure of THA in patients with ONFH, especially in intermediate- to long-term results. For young patients with THA, several surgical treatments are required. Therefore, the head-preserving procedure is the first choice for young patients.

The hip joint is the largest weight-bearing joint of humans,[1] whose pathological progression is closely related to the biomechanics.[2] Several staging and classification criteria,[3–6] including the Japanese Investigation Committee (JIC) classification, Association Research Circulation Osseous system, and the Ficat system, were developed and used to guide treatment of ONFH. However, none of these disease evaluation criteria take into account biomechanical basis limits. Therefore, the situation where selection of treatment is solely based on isolated observation of images is in urgent need of improvement.

This study used computational biomechanical technology to investigate the damage patterns of different classifications of ONFH based on the JIC classification. Our results provide a specific biomechanical basis for treatment decisions of each subtype.

Methods

JIC classification

In 2001, Sugano et al.[7] revised diagnostic criteria to clarify the definition of ONFH. According to the JIC classification criteria, ONFH is classified into subtypes A, B, C1, and C2, which are based on the location of the lesion in the weight-bearing area (Figure 1 and Table 1).

Computational models

Five computational models were constructed according to the JIC classification. Clinical data were used to stimulate a healthy femoral head and create four classifications of a necrotic femoral head in a mid-stance gait cycle. Seven muscles were considered as axial connectors and muscle

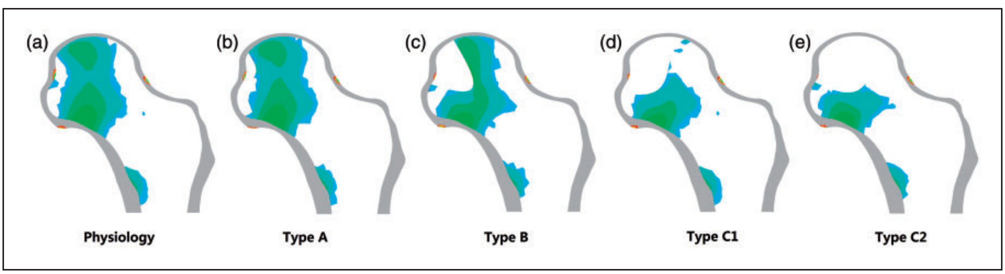

Figure 1. Diagram of the Japanese Investigation Committee classification system.[7]

Table 1. Japanese Investigation Committee classification of osteonecrosis of the femoral head.

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 without extending laterally to the acetabular edge
Type C2	Type C2 lesions occupy more than the medial two-thirds of the weight-bearing portion and extend to the acetabular edge laterally.

forces as previously reported.[8] The endpoint of muscles and cortical bone was connected. The assumed plane load was considered as a ground reaction force that was equivalent to body weight, with application to a rigid plate that was attached to the distal part of the femur. All models are described as nonlinear isotropic elastic models and were input to ABAQUS V6.13 (Simulia Co., Shanghai, China) to generate isotropic 10-node tetrahedral elements. A single-legged stance was considered as a representative body position for the primary models. Constraints were applied to the pubic symphysis and sacroiliac joint. All six degrees of freedom were constrained to zero.

Results

Damage patterns of the stress transfer path

In this study, the damage pattern of the stress transfer path (STP) was an important indicator for evaluating the deterioration process of ONFH. The contours of the STP were plotted from a coronal section view of the femur during the gait cycle. As shown in Figure 1a, the STP of the physiological femoral head was distributed along the direction of the principal compressive trabeculae from the weight-bearing area to the femoral calcar. The STP loads principal compressive stress. The STP of type A showed a strong similarity to the healthy level (Figure 1b, c). The damaged area of principal stress of type B was approximately 25% of the healthy level. The STPs of types C1 and C2 were broken and the damaged area of principal stress was more than 50% of the healthy level (Figure 1d, e). The efficiency of stress transfer was reduced.

Stress distribution of the anterolateral column

Previous research has shown that the risk of collapse of the femoral head is highly correlated with the anterolateral column of the femoral head.[9–11] Therefore, we calculated the average stress of the anterolateral column from all anterolateral elements. Figures 2 and 3 show the relationship between average stresses of the anterolateral column and the deterioration process of ONFH. The average stress increased with an increase in necrotic region. In type A, the average stress was similar to that measured at the healthy level. In type B, the average stress was approximately 4.5% higher than that at the healthy level. The average stress was 17.4% higher in type C1 and 37.5% higher in type C2 than the healthy level. These findings indicated that the risk of collapse of the femoral head in type C was increased.

Validation of the models

For validation purposes, the model was subjected to a reaction force that was equivalent to body weight. The principal STP of this model showed strong similarity to previous results in the literature[8] and to the bone density distribution in a cross-section of a healthy cadaveric femur.[12] Therefore, the biomechanical behaviour of this model was considered valid.

Discussion

The Japanese Investigation Committee revised the classification criteria for diagnosis and management of ONFH in 2001. ONFH is classified into four types, based on the location of the necrotic region by radiological evidence. The hip joint is the largest weight-bearing structure, in which pathological progression is closely related to the biomechanics. However, treatment options based on isolated observation by images without biomechanical basis are required. We postulate that bone necrotic deterioration would destroy the STP and increasingly reduce the stress transfer efficiency of principal compressive trabeculae. Because the four types of ONFH have different biomechanical characteristics, target treatments of types may achieve better clinical efficacy. To test this hypothesis, we created five necrotic damage models to examine the damage patterns of the STP and the risk of collapse of the anterolateral column.

The current study aimed to investigate the damage pattern of the STP for JIC classification of pre-collapse ONFH to provide specific biomechanical basis for treatment decisions of each subtype. Many biomechanical studies have reported ONFH.[13–18] Results from biomechanical models considering damage patterns of STP in different classifications have not been previously published. Using five computational models, we found qualitative damage patterns of the STP and a quantitative risk of collapse of the anterolateral column. There was a rise in damage to the STP with increasing necrotic trabecular region (Figure 2). These results indicate that when the femoral head with necrotic lesions is more than two-thirds of the weight-bearing portion, the principal STP will break off and the stress transfer efficiency may be reduced by half. The risk of collapse of the anterolateral column increased by nearly four times higher when necrotic lesions did not extend to the acetabular edge laterally. The risk of collapse of the

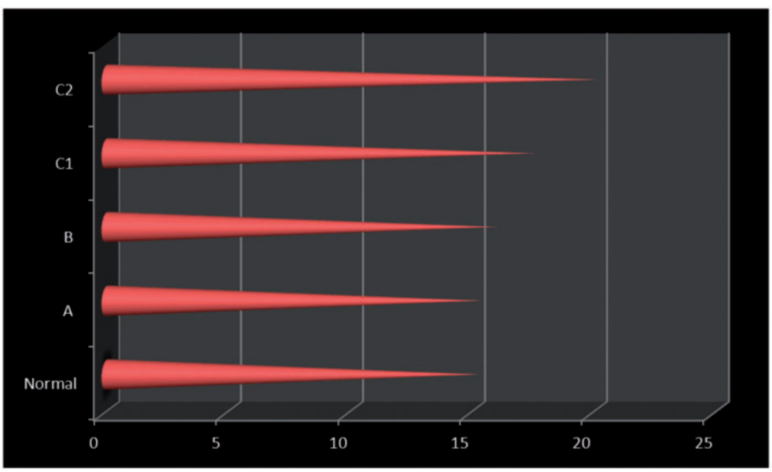

Figure 2. Stress transfer path of the femoral head.

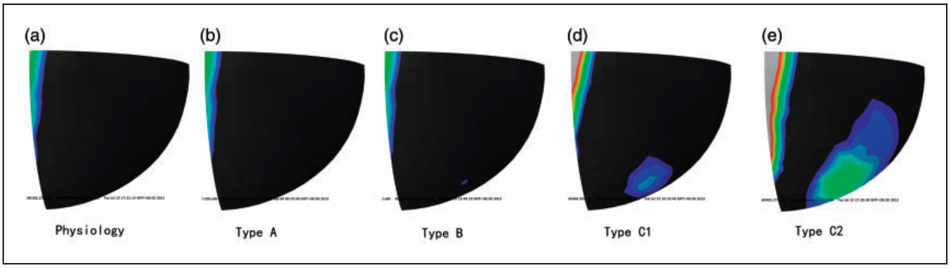

Figure 3. Average stresses of the anterolateral column.

anterolateral column increased to more than eight times higher when necrotic lesions extended to the acetabular edge laterally (Figure 3). These findings indicate that the femoral head lost bearing capability. This may have been caused by the necrotic region losing the ability to load stress, while cortical bone must be overloaded with work to retain morphology and function of the femoral head. When necrotic lesions of the femoral head were between one-third and two-thirds of the weight-bearing portion, the damaged area of the STP was less than 25%. The risk of collapse of the anterolateral column was only increased by 4.5%. These findings indicate that the femoral head still has the function of bearing weight. When necrotic lesions of the femoral head were less than one-third of the weight-bearing portion, the STP was still in good condition. There was no risk of collapse in the anterolateral column.

Conclusions

This study supports use of computational biomechanical technology for investigating the damage patterns of different classifications of ONFH based on the JIC classification. Our study shows that damage patterns of the STP are closely related to classification of the necrotic femoral head. The efficiency of the STP is reduced with an increase in necrotic region. In the early stage of ONFH, such as type A/B, biomechanical behaviour shows little change compared with the healthy femur, which indicates that conservative treatment may be used. However, the STP is broken and the risk of collapse of the anterolateral column increases in the later stage of ONFH, such as type C1/C2. This finding indicates that surgical treatment may be used in this situation.

Authors' Information

Ying Zhang and Kewei Tian: co-first authors.

Declaration of conflicting interest

The authors declare that there is no conflict of interest.

Funding

In support of the research for this manuscript, the authors received grants from the National Science Foundation of China (81473704), the Natural Science Foundation of Henan Province (162102310364), Special Subject of Chinese Medicine Research in Henan Province (2016ZY2027), Special Subject of Chinese Medicine Research in Henan Province (2015ZY02061), and the Natural Science Foundation of Guangdong Province (2014A030 310214).

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