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Reconstruction of the biomechanical transfer path of femoral head necrosis: A subject-specific finite element investigation

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ABSTRACT

According to Wolff's law, the structure and function of bone are interdependent. The disruption of trabeculae in the necrotic femoral head destroys the biomechanical transfer path, increasing the risk of a collapse in the cortical bone. Hence, biomaterials are needed to promote osteogenesis to aid in the reconstruction of a similar biomechanical transfer path that can provide structural and biomechanical support to prevent and delay bone deterioration. Fibular allograft combined with impaction bone grafting (FAIBG) is a hip preservation method that provides both biological repair materials and biomechanical support. This method has been used successfully in the clinical setting, but it still lacks biomechanical insight. In this paper, we aim to provide a biomechanical basis for treatment using FAIBG, we used subject-specific finite element (FE) methods to analyse the biomechanical transfer characteristics of six hip models: physiological, pathological and postoperative. The physiological model provided insight into the biomechanical transfer characteristics of the proximal femur. The pathological model showed an abnormal stress distribution that destroyed stress transfer capability. The postoperative model showed that FAIBG can reconstruct the biomechanical transfer path of the femoral head and reduce the risk of a collapse in the cortical bone. In conclusion, FAIBG seems to treat necrosis of the femoral head.

1. Introduction

Femoral head necrosis (FHN), also referred to as avascular necrosis, is a common debilitating disease in orthopaedics [1]. FHN damages the biomechanical transfer path and causes a collapse in the femoral head, most typically in patients between 20 and 50 years of age (average 36 years) [2]. Various hip preservation procedures have been developed to maintain or reconstruct the mechanical environment and prevent the destruction of the joint, averting the need for a second surgery (i.e., arthroplasty). These procedures include non-operative treatments, core decompression, and free vascularised fibular grafting. However, non-operative treatments have no role in repairing the mechanical environment and show limited success in preventing necrotic progression, even in early stages (i.e., ARCO IIB/IIC). Isolated core decompression will accelerate a collapse in the femoral head, which is associated with a lack of osteogenesis and structural and biomechanical support in the necrotic region [3,4]. Free vascularised fibular grafting can provide immediate structural support and vascularity, but it is often associated with serious trauma, prolonged operation times and high complication rates in the lower limbs [5,6].

According to Wolff's law, the structure and function of bone are interdependent [7]. The disruption of trabeculae in a necrotic femoral head destroys the biomechanical transfer path leading to a failure in mechanical support. Therefore, there is an increased risk of a collapse in the cortical bone. Hence, biological repair materials are needed to promote osteogenesis during the healing of the necrotic region and struct-graft is needed for the reconstruction of a similar biomechanical transfer path to provide structural and biomechanical support.

Fibular allograft combined with impaction bone grafting (FAIBG) is a type of hip preservation surgery that permanently reduces the risk of a collapse in the femoral head by maintaining internal stability of the femoral head and reconstructing the biomechanical transfer path. The FAIBG process provides both biological repair materials and structural support. However, these conclusions have been drawn primarily from observational clinical experience.

Finite element (FE) analysis is expected to provide biomechanical insights into treatment results. Thus, to provide a biomechanical explanation for the effectiveness of FAIBG, we analysed biomechanical

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transfer characteristics of loading in six hip models including physiological, pathological and postoperative models.

2. Materials and methods

2.1. Staging selection

In the ARCO staging system [8,9], ARCO II observed without a collapse in the femoral head is divided into subtypes IIA (medial), IIB (Central) and IIC (lateral), based on the location of the lesion in the weight-bearing area. A type IIA lesion is defined as a lesion located inside of the weight-bearing area with less than 15% necrosis in the femoral head. A type IIB lesion is defined as a lesion located in the centre of the weight-bearing area with between 15% and 30% necrosis in the femoral head. A type IIC lesion extends laterally to the acetabular edge with more than 30% necrosis in the femoral head. Recent studies have shown that ARCO IIB/IIC need surgical intervention because the risk of a collapse in the femoral head is quite high. Hence, this study will focus on analysing the effect of FAIBG on the biomechanical transfer path of ARCO IIB/IIC FHN.

2.2. Development of the physiological and pathological models

ARCO IIB and ARCO IIC models of the ilium–femur–muscle complex (Fig. 1) were developed from CT (0.5-mm thickness) and MRI (0.5-mm thickness) scans of a 32-year-old male volunteer with a mass of 70 kg and height of 173 cm who was diagnosed with ARCO IIB FHN (P1) and A 29-year-old male volunteer with a mass of 60 kg and height of 170 cm who was diagnosed with ARCO IIC FHN (P2) (Fig. 1). Because CT and MRI techniques can make subject-specific simulations of FHN feasible [10–13], we leverage the advantages of CT and MRI to generate a precise model by image fusion technology. CT is considered the most sensitive method for identifying cortical and cancellous structures, while MRI is beneficial for identifying a necrotic region. The CT dataset was used to identify anatomical cortical and cancellous structures, and the MRI dataset was used to identify the lesion zone with MIMICS 15.1. The interface between the ilium and the femoral head was used to identify cartilage geometry. We simulated the physiological and the pathological model using different material properties (Fig. 2) based on the patients' hip geometry.

2.3. Development of a postoperative model

FAIBG represents an established technique for treatment of the early stages of FHN. This study generated a geometric model of a postoperative bone tunnel and fibula. For the simulation of the allogeneic fibular implant, dimensions (80 mm in length and 12 mm in diameter) were obtained from the manufacturer. The entrance point was located in the trochanteric lateral cortex of the femur. The distance of the cortical bone from the apex of the implant was 5 mm. The allogeneic cancellous bone was impacted

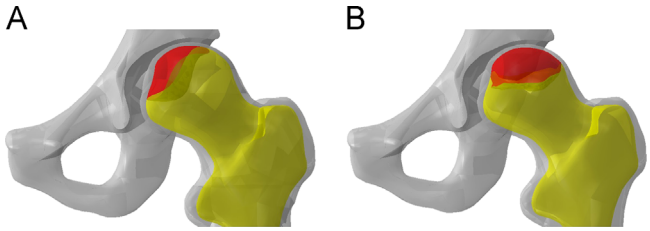

Fig. 1. Three dimensional model of ARCO IIB/IIC (Typical X-ray of ARCO II shows no collapse and the lesion location of the femoral head necrosis: (1) IIB: Central, (2) IIC: Lateral. Necrotic extent: IIB: 15–30% of the femoral head, IIC: >30% of the femoral head.).

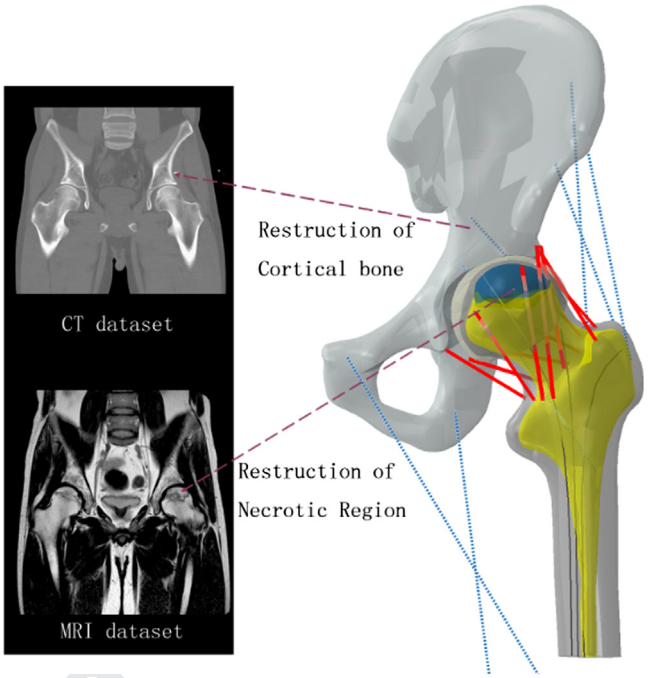

Fig. 2. Development of the pathological model (The contour of cortical bone and cancellous bone are extracted from CT datasets, and the contour of the lesion was extracted from MRI datasets. The interface between the ilium and femoral head was used to identify cartilage geometry.).

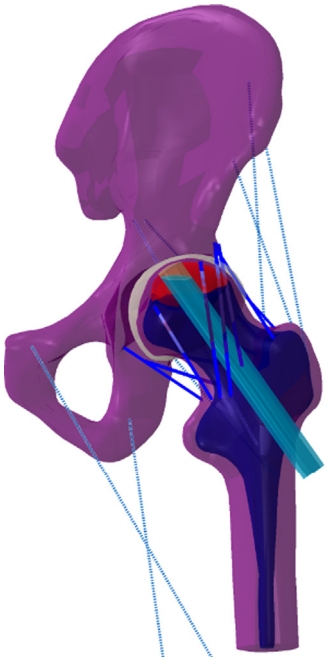

Fig. 3. Development of postoperative model.

into the bone tunnel between the cortical bone and the top end of the graft fibula complex (Fig. 3).

2.4. Material properties

For the three-dimensional models defined above, solid elements (tetrahedral element) were chosen to represent the bone and cartilage tissue. The following material properties of cortical bone, trabecular bone, cartilage and lesion bone were obtained from the literature [14–16]: $E_{cortical}=15100$ MPa, $E_{trabecular}=445$ MPa, $E_{cartilage}=10.5$ MPa, $E_{lesion}=124.6$ MPa; $\nu_{cortical}=0.3$, $\nu_{trabecular}=0.22$, $\nu_{cartilage}=0.45$ and

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