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Biomechanical effects of bone-implant fitness and screw breakage on the stability and stress performance of the nonstemmed hip system

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ABSTRACT

Background: Some nonstemmed hip systems have been developed to avoid stress shielding and aseptic loosening, which are major drawbacks of stemmed hip arthroplasty. Without the stem, the cup over the femoral head can be stabilized by anatomic fitness of the cup interior and mechanical fixation of the auxiliary screws.
Methods: Using finite-element method, neck-shaped systems with two bone-cup fitness situations and four types of screw breakages are systematically investigated to evaluate their biomechanical effects on construct performances. The construct stresses and interfacial micromotion were chosen for comparison between two bone-cup fitness situations and four types of screw breakages.
Findings: The screw breakage deteriorates the stresses of the mating screw and the neck cup and loosens the bone-cup interfaces. The breakages of central and locking screws decrease the bone stress by about 43.2% and 12.7%, respectively. This indicates that the central screw is a more effective load-bearer for the superimposed cup than the locking screw. As compared with the fitting cup, the stress of cup and the bone stresses of the unfitting cup obviously increase. This demonstrates that the load-transferring path at the cup bottom is important in directly relieving the prosthetic stresses.
Interpretation: Any screw design inducing stress concentration should be validated to avoid screw breakage. Comparatively, surgical unfitness has a more significant effect on the construct performance than does the screw breakage. Even for custom-made cups, cautious preparation of the neck resection is still necessary to ensure intimate bone-cup contact.

1. Introduction

Total hip replacement (THR) with a metallic stem has been extensively used to treat various hip diseases in patients over the age of forty (Callaghan et al., 1998; Chiu et al., 2001; Keener et al., 2003). The surgical method of stemmed THR is to amputate the intact femoral neck entirely, rasp off the intramedullary canal, and evacuate the bone marrow for the stem insertion. However, the mass removal of the bone stock necessitates the transfusion of much more blood, which might lead to post-operative infection and technical difficulty in revision surgery (Callaghan et al., 1998; Chiu et al., 2001; Epinette and Manley, 2003; Keener et al., 2003; Park et al., 2003). In general, there are three types of the stem-induced complications affecting the long-term THR results. The first is bone resorption (osteolysis) that the wear debris penetrates into the intramedullary canal and induces a chemical reaction of the immune system (Orishimo et al., 2003). Another is bone loss (osteoporosis) that the loads of the proximal femur are shielded by the inserted stem, potentially resulting loosening of the implant and even bone fracture (Bugbee et al., 1997; Chen et al., 2004a; Joshi et al., 2000; Maloney et al., 2002; Padgett and Warashina, 2004; Shih et al., 1997; Tai et al., 2004). The third is impingement of the stem end which has been reported as a stress raiser inducing fracture of the diaphysial cortex (Epinette and Manley, 2003).

If the hip defects of younger or more active patients are limited to the superficial regions of the femoral head, some studies have suggested preserving the bridging bone stock (femoral neck) between the femoral head and the diaphysial shaft (Chen et al., 2004b; Lutz et al., 2010; Mont and Hungerford, 1995; Siguier et al., 2001). In the literature, some

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nonstemmed systems have been developed and evaluated by numerical or experimental methods to remove femoral head and preserve neck without using a metallic stem into intramedullary canal (Chen et al., 2009; Maloney et al., 2002; Munting and Verhelpen, 1995; Padgett and Warashina, 2004; Tai et al., 2003). These studies consistently demonstrate that the proximal region of the nonstemmed femur shows a more physiological pattern of stress distribution than do stemmed systems (Maloney et al., 2002; Padgett and Warashina, 2004; Tai et al., 2003). From the biomechanical viewpoint, the reported advantages of nonstemmed systems over their counterparts are attributed to the preservation of both the femoral neck and intramedullary canal. Without stem support, however, the failure (*e.g.* loosening and breaking) of the hip prostheses and the instability of the bone-implant construct have been reported as the major concerns of nonstemmed system (Adams and Quigley, 2005; Amstutz et al., 2007).

Historically, the nonstemmed systems can be divided into two types: femoral ball- shaped and neck-shaped cups (Barrett et al., 2006; Tai et al., 2003). For ball-shaped systems, the cup interior is of a cylindrical shape and the cup bottom is mounted by a metallic shaft to strengthen the bone–cup stability. During surgery, the femoral head is reamed as a cylinder to fit the ready-made diameter of the cup interior. For neck-shaped cups, the femoral head is cut and the cup covers the femoral neck to transfer the loads from the hip to the neck. In general, there are two designs of neck-shaped cups: ready-made and custom-made (Qi et al., 2004; Tai et al., 2003). For the ready-made design, the cup interior is often cylindrically in shape, thus the femoral neck is intra-operatively reamed to fit the cup design (Qi et al., 2004). Using an axial reamer, however, the remaining cancellous core and cortical shell of the irregular neck might not fully contact with the cup interior (Duan Mu et al., 2005).

From the biomechanical viewpoint, the femoral neck is subjected to the combined loads, potentially leading to sliding, bending, and twisting of the superimposed cup. However, the cylindrical interior of the neck cup can only resist bending and inefficiently prevent sliding and twisting along the neck axis (Duan Mu et al., 2005). Additionally, the weaker strength of a shaped cancellous-dominate neck might not provide the long-term stability to a highly loaded cup. Consequently, clinicians often find it necessary to use screws to further stabilize the bone–cup construct (Qian et al., 2003; Wang et al., 2004). In the literature, the reported long-term complications of two ready-made cups include the construct instability at the bone–cup interfaces and mechanical failure of the screw and cup shaft (Adams and Quigley, 2005; Amstutz et al., 2007; Lin et al., 2006).

The CT-scanning images have been used as the shape reference to design personalized neck cup that can intimately fit the peripheral cortex of the preserved neck (Viceconti et al., 2001). The biomechanical merits of anatomically fitting cup include the initial stability of the cup itself, the stronger support of the neck cortex, and less influence on the femoral biomechanics (Huang et al., 2010). Even with anatomical fitness, the bone–cup construct is further stabilized by using screws to link the bone and the cup (Munting and Verhelpen, 1995; Qian et al., 2003; Tai et al., 2003). Several cup–screw mechanisms have been proposed and detailed comparisons between them have yet to be extensively investigated (Viceconti et al., 2001). This constitutes the major motive of the current study.

This study aims to investigate two topics of hip hemiarthroplasty using a personalized neck-shaped cup: the effects of both bone section and screw breakage on the construct performance. Based on the CT-images, the finite-element model of the intact femur is developed and subjected to hip compression and muscular contractions. The neck cup is instrumented onto the resected neck and two screws are used to enhance the construct stability. The improper resection at the bone–cup interface and the breakage of the highly stressed screws are simulated to evaluate surgery- and screw-induced effects on the construct performance. The stress distribution and interfacial micromotion along the specific lines of the bone–cup and screw surfaces are compared among the different constructs. The results of this study are expected to provide insight into the load-transferring and interface-slipping mechanisms of personalized neck-cup system.

2. Methods

2.1. Femoral model and hip prostheses

A 24-year-old male subject without any hip disease takes part in computed tomography (CT) scanning of pelvis and femur (120 kVp, 160 mAs, axial scan, 1-mm spanned slices, and 0.781-mm/pixel resolution) and only proximal femur was used in this study. The outlines of each CT-scanning slice are recognized and three-dimensionally reconstructed as the proximal femur with triangular surface meshes using the software PhysiGuide, version 2.3.1 (Pou Yuen Technology Co., LTD, Changhua, Taiwan) (Huang et al., 2010). The threshold values of the gray scale are from 260 to 1500 for cortical bone and from 30 to 320 for cancellous bone, respectively. The femur consists of a cortical shell and a cancellous core and their boundaries are defined from the gray-scale difference of the CT-image outlines. The femoral model is further transformed into a solid model with smooth and seamless surfaces using the software SolidWorks, version 2012 (SolidWorks Corporation, Concord, MA, USA).

The current authors use the aforementioned femur to design a personalized cup that is highly fitting with the subject's neck (Fig. 1A). This study uses the term “cup” to indicate the cup over the femoral head rather than an acetabular cup. During surgery, however, the bone–cup interfaces at the line *AA* could not always ensure as the intimate contact and potentially decrease the load-transferring ability at the fit-cup bottom (Fig. 1A). A central screw is used through the anatomical axis of the femoral neck to further stabilize the fitting cup (Fig. 1B). If necessary, the locking screw can be used to link the two screws as a stability-enhancing mechanism for the bone–cup construct. However, the hole of the central screw and the corner of the locking screw serve as the sites of geometric discontinuity. The cup slot is designed for avoiding direct compression to the periarticular blood vessels and nerve roots (Fig. 1B). Consequently, the mechanical failure of those sites is one of the major concerns of this nonstemmed system.

This study develops eight variations to investigate the effects of two bone–cup fitness situations and four types of screw breakage on construct stability and implant failure (Fig. 2). Two variations of bone–cup fitness indicate whether the fit-cup bottom makes intimate contact with the resected neck at the line *AA* or not (Fig. 2A). The symbols IF and SU denote ideal fitness and surgical unfitness, respectively. The term “surgical unfitness” indicates the interfacial gap between bone and cup by a surgeon. Four variations of screw breakage define the situations that mechanical failure occurs between the central screw and the locking screw (Fig. 2B). Eight variations (IF1, IF2, IF3, IF4, SU1, SU2, SU3, and SU4) include two bone–cup fitness (*i.e.* IF and SU) and four screw breakage (numbers 1, 2, 3, and 4). The numbers 1, 2, 3, and 4 indicate the situations of no screw breakage, only locking screw breakage, only central screw breakage, and breakage of two screws, respectively.

2.2. Finite-element analysis

The physiological loads of hip compression and muscular contractions are applied onto the proximal femur and the distal end is rigidly fixed (Fig. 3A). The *X-Y-Z* coordinate system with the origin at the knee intercondyle is used to define the muscular contractions. The *X*, *Y*, and *Z* axes are mediolaterally, anteroposteriorly, and superoinferiorly directed, respectively. The insertion points and force directions of the gluteus, piriformis, iliopsoas, ilio-tibial tract, vastus lateralis, and adductor are cited from the values found in previous studies (Brand et al., 1986; Duda et al., 1996; Huiskes and Boeklagen, 1989). The vectorial components of the hip and muscle forces on the femur are selected at the static position of one leg stance (Shih et al., 2008;