Medical Engineering and Physics 39 (2017) 23–30

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Biomechanical optimization of the angle and position for surgical implantation of a straight short stem hip implant

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ARTICLE INFO

Article history:
Received 17 March 2016
Revised 15 August 2016
Accepted 9 October 2016

Keywords:
Biomechanics
Stress
Short-stem
Hip arthroplasty
Finite element analysis

ABSTRACT

Conservative hip implants preserve healthy bone for revision surgeries and improve physiological loading; however, they have little supporting biomechanical data with respect to their 3D orientation during implantation. This study endeavored to determine the optimal 3D orientation of a straight short stem hip implant within the proximal femur that would yield a stress distribution most similar to an intact femur.

Synthetic femurs were implanted with a stem in one of seven maximum angles or positions and axially loaded, with resultant strain values used to validate a finite element model. Design of experiments was used to analyze the range of potential implant orientations under three gait cycle loading conditions.

A global optimal orientation of 9.14° valgus, 2.49° anteversion, 0.48 mm posterior position, and 0.23 mm inferior position was found to yield stress distributions most similar to the intact femur across the gait cycle range. In general, it was determined that the valgus orientation was optimal throughout the gait cycle, consistently exhibiting a stress distribution more similar to that of the intact femur. Minimal levels of anterior/posterior and inferior positioning were seen to be beneficial in achieving more physiological stresses in specific regions of interest within the proximal femur, while the anteverted orientation was only beneficial in loading under flexion.

Overall, orthopaedic surgeons should aim to implant straight short stem hip implants in valgus up to 10°, with an otherwise neutral position and version, unless some degree of deviation would be beneficial for a patient-specific reason. This work has implications for the best surgical placement of straight short stem hip implants to yield maximal biomechanical stability.

1. Introduction

Total hip replacements (THR) are becoming increasingly popular in the younger, more active population. However, the 10-year survivorship of hip implants in young patients is low due to aseptic implant loosening, requiring patients to undergo revision surgery to remove and replace the failed implant [1]. Secure fixation of the revision component is crucial to ensuring long-term survivorship of the new implant. Traditional hip implants extend into the femoral metaphysis/diaphysis and are cemented or undergo osseointegration, making them difficult to remove. This often makes stable fixation of a revision component challenging to achieve proximally, as this bone stock tends to be deficient and weak from the previous implant [2]. Conservative implants preserve more healthy proximal bone stock for revisions, improve physiological loading of the hip [3–5], and minimize "stress shielding," which leads to bone resorption and implant loosening [6–9]. Mid-term clinical results for conservative hip implants show good initial stability, with more physiological loading, less bone resorption, and good implant survival rate [3,5,10–12]. However, few biomechanical studies have assessed ideal implant orientation. Thus, this study experimentally and computationally determined

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http://dx.doi.org/10.1016/j.medengphy.2016.10.002
1350-4533/

the optimal 3D angle and position of a short stem hip implant within the proximal femur.

2. Methodology

2.1. General method

Biomechanical experiments were performed on an implanted Silent Hip (DePuy, Leeds, UK) under subclinical loads to generate strain values and validate a corresponding finite element (FE) model. For three key points in the gait cycle, design of experiments (DOE) was used to evaluate the FE model over the range of potential implant angles and positions, and determine the optimal 3D implant orientation with stresses most similar to the intact femur.

2.2. Biomechanical testing

2.2.1. Implant orientation

The Silent Hip (DePuy, Leeds, UK) is a modular, cementless conservative hip implant, featuring a straight short stem with a collarless tapered profile for implantation in the femoral neck. This device can be implanted in an infinite combination of angles and positions. To validate the FE model, seven experimental implant orientations were tested, corresponding to the maximum implant angulations and translations achievable without breaching cortical bone, thus allowing for a clinically feasible press-fit insertion [13].

The neutral orientation maintained the natural collum-caput-diaphyseal (CCD) angle of the synthetic femur in the anteroposterior (A/P) view, and a neutral lateral angle and position (Fig. 1). From the neutral orientation, 3 maximum angles were determined: valgus, varus, and anteversion. Given the natural synthetic femur CCD angle of 120 °, maximum valgus was 130 °, while maximum varus was 110 °. Maximum anteversion was a stem-neck angle of 10 ° when viewed in the lateral plane. There were 3 maximum positions defined from the neutral orientation: anterior, posterior, and inferior. In the lateral view, maximum anterior was 2 mm anterior to the neutral line, while maximum posterior was 2 mm posterior. The maximum inferior position was 4 mm distal to the neutral CCD angulation in the A/P plane. It was determined that a deliberately retroverted implant angle may lead to further retroversion, loosening, or failure [14], while deliberate superior positioning could lead to leg length discrepancy [15]; therefore, these configurations would seldom be surgical goals and were excluded.

2.2.2. Femur preparation

Ten large, left, fourth-generation composite femurs with identical geometries and material properties were used (Model #3406, Pacific Research Laboratories, Vashon, WA, USA). Femurs had a head diameter of 52 mm, total length of 485 mm, intramedullary canal diameter of 16 mm, cortical bone density of 1.64 g/cm^3, and "solid type" cancellous bone density of 0.27 g/cm^3. Synthetic femurs, rather than human cadaveric femurs, were chosen since they have lower interspecimen variability [16]. Based on the synthetic femur dimensions, an ideally sized Silent stem of 22 mm diameter and 50 mm length was implanted using a hybrid surgical methodology that included imageless computer navigation (BrainLAB, Feldkirchen, Germany) for initial implant alignment [17], followed by the Silent Hip surgical technique [18]. The stem was implanted in six femurs each representing a predetermined non-neutral implant orientation, three femurs were used for the neutral implant orientation to establish repeatability, and one femur remained intact as a baseline, thus, totaling 10 femurs. Following condyle resection, femurs were angled to simulate single-leg stance (adduction = 7 °, flexion/extension = 0 °) and potted in cement-filled steel cubes [19,20].

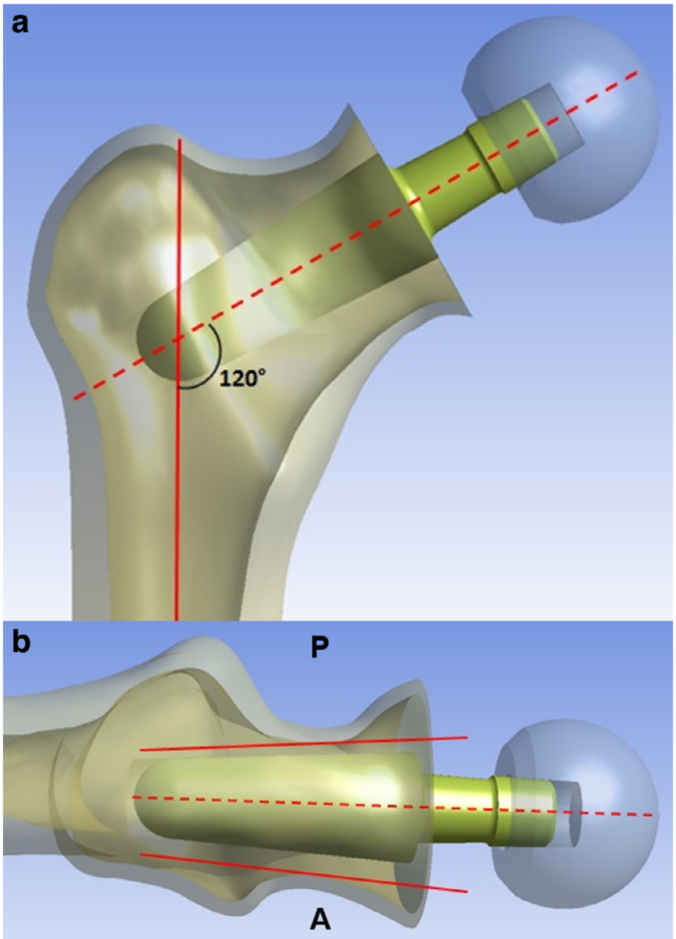

Fig. 1. Silent Hip neutrally implanted in the femur, showing: (a) A/P view, where the solid red line indicates the long axis of the femur and the dashed line represents the implant axis at a CCD angle of 120 °; (b) lateral view, where the neutral angle and position are illustrated through the central location of the stem between lines tangent to the cortical bone.

2.2.3. Strain gauge placement

Femurs were instrumented with five 350Ω uniaxial linear strain gauges (Model CEA-06-125UW-350, Vishay Measurements Group, Raleigh, NC, USA) and one 350Ω rectangular rosette gauge (Model CEA-125UY-350, Vishay Measurements Group, Raleigh, NC, USA). Two linear gauges were placed on the medial femoral shaft and three on the lateral shaft, while the rosette gauge was attached proximally on the anterior side of the femur (Fig. 2a). Wire leads soldered to each strain gauge were attached to an 8-channel Cronos-PL data acquisition system (IMC Mess-Systeme GmbH, Berlin, Germany), which was in turn networked with a computer for data storage and analysis (FAMOS V5.0 software, IMC Mess-Systeme GmbH, Berlin, Germany).

2.2.4. Loading conditions

To mimic physiological stresses in the proximal femur [21], the three neutrally implanted femurs also underwent testing at hip angles approximating the maximum bounds within a gait cycle [22–24], namely, 15 ° of sagittal plane hip flexion to simulate heel strike and 15 ° of hip extension to simulate toe-off, as well as at 0 ° to simulate full single-leg stance like the non-neutrally implanted femurs and the intact femur. Femurs were rigidly fixed at their distal potted end into an industrial vice mounted to the baseplate of an Instron 8874 tester (Instron, Norwood, MA, USA) (Fig. 2a). The load cell had a ±25 kN capacity, 0.1 N resolution, and ±0.5% accuracy. Femurs were vertically preloaded with