Journal of Biomechanics 49 (2016) 1064–1070

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

The influence of contact ratio and its location on the primary stability of cementless total hip arthroplasty: A finite element analysis

M. Reimeringer*, N. Nuño

Laboratoire de recherche en imagerie et orthopédie, Département de génie de la production automatisée, École de technologie supérieure, 1100 rue Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

ARTICLE INFO

Article history:
Accepted 12 February 2016

Keywords:
Total hip arthroplasty
Finite element analysis
Contact
Micromotion
Cementless stem

ABSTRACT

Cementless hip stems are fixed to the surrounding bone by means of press-fit. To ensure a good press-fit, current surgical technique specifies an under-reaming of the bone cavity using successively larger broaches. Nevertheless, this surgical technique is inaccurate. Several studies show that the contact ratio (percentage of stem interface in contact with bone) achieved after surgery can vary between 20% and 95%. Therefore, this study aimed to investigate the influence of the contact ratio and its location on the primary stability of a cementless total hip arthroplasty using finite element analysis. A straight tapered femoral stem implanted in a composite bone was subjected to stair climbing. Micromotion of 7600 nodes at the stem-bone interface was computed for different configurations of contact ratios between 2% and 98%) along the hip stem. Considering the 15 configurations evaluated, the average micromotion ranges between 27 μm and 54 μm. The percentage of the porous interface of the stem having micromotion below 40 μm that allows bone ingrowth range between 25–57%. The present numerical study shows that full contact (100%) between stem and bone is not necessary to obtain a good primary stability. The stem primary stability is influenced by both the contact ratio and its location. Several configurations with contact ratio lower than 100% and involving either the proximal or the cortical contact provide better primary stability than the full contact configuration. However, with contact ratio lower than 40%, the stem should be in contact with cortical bone to ensure a good primary stability.

1. Introduction

Total hip arthroplasty (THA) is one of the most successful surgical procedures and remains the treatment of choice for long-term pain relief and restoration of function for patients with diseased or damaged hips. THA consists in removing head and neck of a femur and replacing them by a prosthesis. Two types of prosthetic devices are used: cemented and cementless stems. Cemented stems are fixed to the surrounding bone by means of bone cement, whereas cementless stems are fixed to the surrounding bone by means of mechanical press-fit. No significant difference between cemented and cementless THR in terms of implant survival as measured by revision rate has been found (Abdulkarim et al., 2013), and debate still exists regarding the optimal fixation methods. Nevertheless, today cementless fixations are generally preferred (Learmonth et al., 2007), especially in young and active patients, to eliminate problems associated to the use of cement (Jasty et al., 1991).

Primary stability achieved after surgery is a determinant factor for the long-term stability of cementless hip arthroplasty. The term primary stability has been defined by Viceconti et al. (2006) as the amount of relative micromovement between the bone and the implant induced by the physiological joint loading early after the operation, before any biological process takes place. The presence of motion at the stem-bone interface leads to formation of fibrous tissue that can prevent bone ingrowth, which in turn may lead to loosening of the implant (Viceconti et al., 2001). Pilliar et al. (1986) have shown that an interfacial micromotion above 40 μm produces partial ingrowth, while micromotion exceeding 150 μm completely inhibits bone ingrowth.

Primary stability depends on many parameters. Many studies have focused their interest on the stem design (Callaghan et al., 1992, Ando et al., 1999; Mandell et al., 2004; Abdul Kadir et al., 2008, Reimeringer et al., 2013; Bah et al., 2015), the sensitivity to hip joint loading (Pancanti et al., 2003), the effect of physiological load configuration (Abdul Kadir and Hansen, 2007), the effect of inter subject variability (Viceconti et al., 2006; Bah et al., 2015), the effect of bone material properties (Wang et al., 2005; Reimeringer and Nuño, 2014).

* Corresponding author. Tel.: +1 514 396 8800x7528.
E-mail address: mickareim@gmail.com (M. Reimeringer).

http://dx.doi.org/10.1016/j.jbiomech.2016.02.031
0021-9290/

Table 1
Contact ratio between the stem and the bone.

	Authors	Stem	Contact area (%)	Contact zone
Traditional broaching method	Paul et al. (1992)	3 Custom stems	20.8	Cortical and cancellous bones
		3 Zimmer BIAS stems	20.8	
	Laine et al. (2000)	50 B-Metric stems	41	Cortical bone
		26 ABG Stems	38	
	Wu et al. (2004)	5 Collarless straight stems	60.1	Cortical and cancellous bones
	Howard et al. (2004)	6 Synergy Stems	43.6	Cortical and cancellous bones
		6 Prodigy stems	57.5	
	Park et al. (2008)	6 Versys stems	67	Cortical and cancellous bones
New broaching method	Park et al. (2008)	6 Versys stems	82	Cortical and cancellous bones
Robotic system	Paul et al. (1992)	3 Custom stems	95.7	Cortical and cancellous bones
	Wu et al. (2004)	5 Collarless Straight stems	93.2	Cortical and cancellous bones
FEA	Monea et al. (2014)	Custom made stem	22.6	Cortical and cancellous bones
		Advanced custom made stem	31.7	
Virtual	Baharuddin et al. (2014)	Custom cementless stem	53.7	Cortical bone

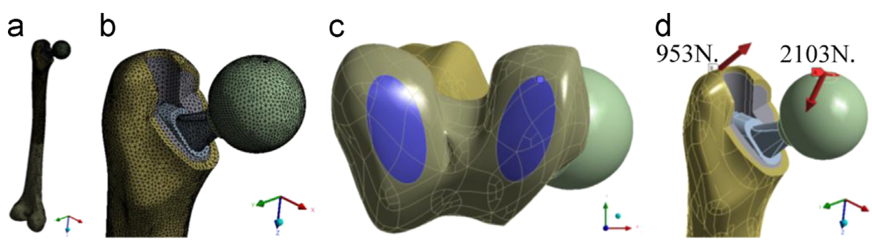

Fig. 1. Finite element analysis pre-processing a) overview of the mesh b) zoom of the proximal mesh c) fixed support d) abductors and joint contact forces.

Another parameter that influences the primary stability is the position of the implant within the bone (Reggiani et al., 2008; Bah et al., 2011). A good primary stability for cementless THA is achieved by a close apposition of the implant to the bone. Its position is determined during the pre-operative planning. During surgery, the canal is manually broached with successively larger broaches until the broach contacts the femoral cortex. Moreover, to ensure a press-fit, the current surgical technique specifies an under-reaming of the cavity. This classical technique is inaccurate (Lattanzi et al., 2003). The contact ratio (percentage of stem interface in contact with bone along the stem) achieved after surgery ranged between 20% and 82% using a broaching method or determined by numerical analysis and can increase up to 95% using a robotic system (Table 1). The lack of direct contact between the stem and the bone has been identified by Viceconti et al. (2006) as the main risk for implant stability. Moreover, Tarala et al. (2013) has shown that bone ingrowth around the hip stem necessary for secondary stability of the implant depends on stem-bone contact area with both cortical and cancellous bones. Nevertheless, Park et al. (2009) indicate that when 40% of contact ratio is achieved along the stem, primary stability is little affected by an increase in this contact ratio.

However it is still not clear how the micromotion (relative movement between stem and bone) varies as a function of the contact ratio and its location along the stem, nor which area promotes more osteointegration. Therefore, this study aimed to investigate the effect of the contact ratio and its location on the primary stability of a cementless stem subjected to stair climbing using finite element analysis (FEA).

2. Materials and methods

Based on an experimental implantation (details can be found in Reimeringer et al., 2013), a virtual implantation of a size 6 Profemur®TL was performed into a composite Sawbones® (Mod. 3406, Pacific Research Laboratory, Inc., Vashon Island, WA, USA) using CatiaV5R19 (Dassault Systèmes, Velizy, Villacoublay, France). The Profemur®TL is a straight taper stem with a lateral shoulder. A plasma spray (coating surface thickness of around 1 mm per side) is present on the proximal part of the stem. The distal part of the stem has a glass-beaded texture. The distal tip ends with a rounded shape to reduce the risk of fracture during the insertion and to minimise point contact after implantation. The mechanical behaviour of the composite Sawbones® has been validated by Heiner (2008) and Gardner et al. (2010). The implant position and orientation have been validated by surgeons in a previous study (Reimeringer et al., 2013).

The 3D model of a full femur was transferred into Ansys Workbench 14.5 (Ansys Inc., Canonsburg, PA, USA) pre- and post-processing programme. A 10-noded tetrahedral mesh was created. Helgasson et al. (2008) studied the sensitivity of the mesh size. They showed that an average mesh size of 3.3 mm is a threshold to obtain satisfactory convergence. Moreover, a minimum of two elements in the thickness of a structure is better to represents its bending behaviour. Thus, a mesh size of 2 mm was generated proximally Fig. 1a and b), whereas a mesh size of 5 mm was generated distally (Fig. 1c), as this region was away from the region of interest. This results in a total of 373 415 elements (91 962 for the prosthesis, 73 587 for the cancellous structure and 207 866 for the cortical structure).

FEA was carried out for the static loading conditions defined by Bergmann et al. (2001), simulating stair climbing as being the critical load case regarding the primary stability (Pancanti et al., 2003; Kassi et al., 2005). The applied resultant forces (calculated with a body weight of 836 N) were 953 N and 2103 N to simulate the abductor muscles and hip joint contact forces, respectively (Fig. 1d). The femoral condyles were assumed to be rigidly constrained (Fig. 1e). The resultant forces were oriented in the coordinate system defined by Bergmann et al. (2001).

All materials were defined as linear isotropic homogeneous. The stem and neck were made of titanium, whereas the head was made of chrome-cobalt, with a Young modulus E of 110 GPa and 210 GPa, respectively. The composite Sawbones is made of two materials: short fibre filled epoxy for the cortical analogue with E of 16.7 GPa and rigid polyurethane foam for the cancellous analogue, with E of 155 MPa. The Poisson ratio ν for all materials was set to 0.3.

Contact between bone and prosthesis was modelled using the augmented Lagrange algorithm with face to face contact element (Viceconti et al., 2000) with the prosthesis as the contact body and the femoral cavity as the target body. The contact between stem and bone was divided into four areas following the surgeon's recommendations (Reimeringer et al., 2013): the proximal plasma spray surface in contact with cancellous bone (Fig. 2a), the middle plasma spray surface in contact with cancellous bone (Fig. 2b), the distal polished surface in contact with cancellous bone (Fig. 2c) and the plasma spray surface in contact with cortical bone (Fig. 2d and e). The proximal contact area represents a contact ratio of 39%, the middle contact area 31%, the distal contact area 28% and the two cortical contact areas 2%. The contact ratio has been calculated by divided the number of node in contact for each area by the total number of node in contact.

To understand the influence of contact ratio and its location on the primary stability, micromotion was first evaluated on a case where the stem-bone interface is in full contact (100%, all four areas). Then, 3 different configurations were