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Short communication

Friction coefficient and effective interference at the implant-bone interface

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ABSTRACT

Although the contact pressure increases during implantation of a wedge-shaped implant, friction coefficients tend to be measured under constant contact pressure, as endorsed in standard procedures. Abrasion and plastic deformation of the bone during implantation are rarely reported, although they define the effective interference, by reducing the nominal interference between implant and bone cavity. In this study radial forces were analysed during simulated implantation and explantation of angled porous and polished implant surfaces against trabecular bone specimens, to determine the corresponding friction coefficients. Permanent deformation was also analysed to determine the effective interference after implantation. For the most porous surface tested, the friction coefficient initially increased with increasing normal contact stress during implantation and then decreased at higher contact stresses. For a less porous surface, the friction coefficient increased continually with normal contact stress during implantation but did not reach the peak magnitude measured for the rougher surface. Friction coefficients for the polished surface were independent of normal contact stress and much lower than for the porous surfaces. Friction coefficients were slightly lower for pull-out than for push-in for the porous surfaces but not for the polished surface. The effective interference was as little as 30% of the nominal interference for the porous surfaces. The determined variation in friction coefficient with radial contact force, as well as the loss of interference during implantation will enable a more accurate representation of implant press-fitting for simulations.

1. Introduction

Press-fitting of prosthesis stems into bone is achieved by insertion of a wedge-shaped implant into a radially smaller cavity to generate friction resistance to relative motion at the interface, thereby allowing bone ingrowth and stable fixation (Engh et al., 1992; Jasty et al., 1997; Ramamurti et al., 1997). Porous implant coatings are used to ensure high friction coefficients against bone and to provide a favourable surface for bone ingrowth (Bobyn et al., 1999; Jamieson et al., 2011; Simmons et al., 1999).

Friction coefficients have been reported for various constant interface pressure magnitudes and also in biaxial tangential force directions (Biemond et al., 2011; Dammak et al., 1997a; Grant et al., 2007; Hashemi et al., 1996; Shirazi-Adl et al., 1993; Zhang et al., 1999). They have been used to model press-fit implant behaviour to assess relative motion at the bone interface and stress distributions in the bone (Abdul-Kadir et al., 2008; Ramamurti et al., 1997). Excessive normal stresses can cause periprothetic fracture during implantation (Dumont et al., 2010; Nowak et al., 2012). Friction coefficients have not been reported for conditions of varying contact stress occurring, for example, during implantation. Representing this stage correctly may be important in setting up models to properly represent the mechanical conditions during the service life of the implant.

Implant surfaces have been shown to generate permanent trabecular bone deformation during simulated press-fit implantations (Bishop et al., 2014), leading to a press-fit interference that is less than the nominal interference between the implant and the cavity. This might explain the use of small interferences in modelling press-fit implantation to prevent unreasonably high stresses in the bone (Abdul-Kadir et al., 2008; Gebert et al., 2009; Rothstock et al., 2010).

The purpose of this study was to investigate the friction coefficient between implant and bone during experimentally simulated press-fit implantation and pull-out, and to estimate the reduction in nominal press-fit interference due to bone deformation.

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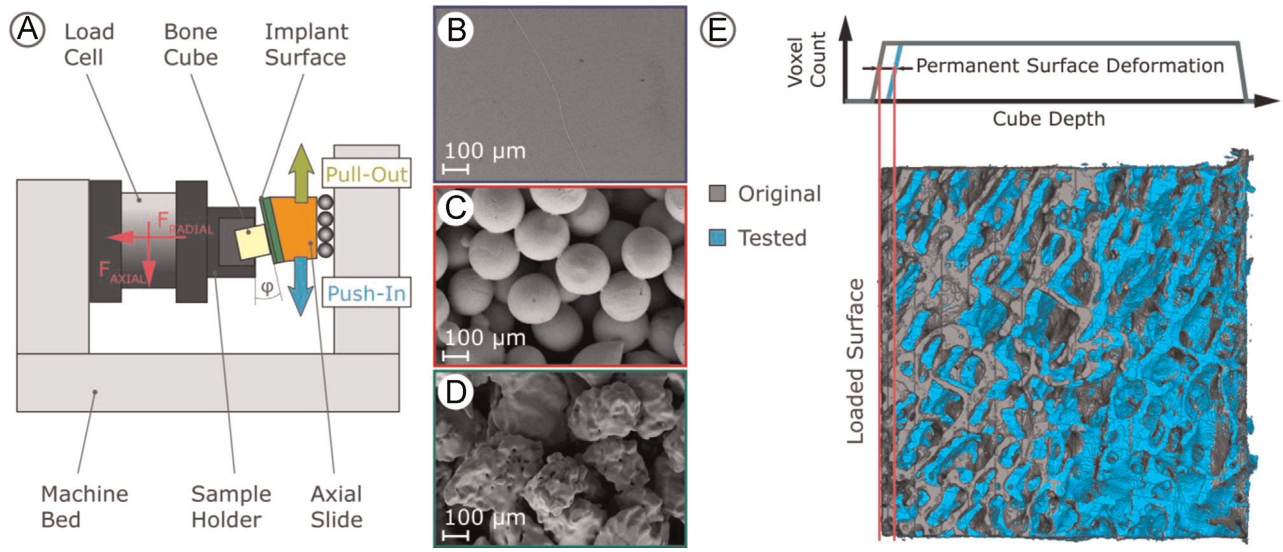

Fig. 1. (A) A schematic of the test apparatus showing a bone specimen mounted on a multiaxial load-cell, and a surface platen mounted at $\varphi=3.5°$ to a linear bearing. (B)–(D) SEM images of the tested implant surfaces: (B) Polished; (C) Beaded; (D) Flaked; and (E) permanent surface deformation determined by superposition of µCT scans with an idealized voxel count curve (example for polished 900 µm).

2. Materials and methods

Data from a previous experiment were used to calculate the friction coefficients and the reduction in interference. The experiment is described briefly in the following section. A detailed description can be found elsewhere (Bishop et al., 2014).

2.1. Original Experiment

Titanium platens (Ø30 mm) were prepared with three commercially available surface finishes: Polished, Porocoat® ('Beaded') and Gription® ('Flaked') (DePuy International Ltd., Leeds, UK, Fig. 1). Surface roughness and porosity are given in Table 1.

Ten millimetre trabecular bone cubes were sectioned from the heads of four pairs of human femora, with normal bone density, and embedded in PMMA cement at an angle φ of 3.5° with the bone surface 4 mm proud of the cement (Fig. 1A). Platens were displaced at 0.05 mm/s to generate nominal radial interferences of 300, 600 and 900 µm, reflecting interferences employed clinically (Gebert et al., 2009; Gililland et al., 2013; Ramamurti et al., 1997; Udofia et al., 2007). Pull-out was performed directly after implantation at the same rate. Zero position was defined by an initial 5 N contact force measured in the radial direction. For each implant surface and interference $n=3$ measurements with fresh platens and bone samples were made. Force and displacement measurements were sampled at 50 Hz.

Micro-computed tomography (µCT) scans of the bone cubes before and after loading were reconstructed and superimposed and the permanent deformation of the loaded surface was determined from the difference between surface positions in the direction normal to the platen surface (Fig. 1E). The surface of the specimens was defined by the inflection point of the section-wise total voxel count curve of the slices parallel to the tested bone surface calculated from a volume of interest around the centroid of the cube, containing 80% of tested surface and full depth (MATLAB, R2014a, The MathWorks Inc., Natick, MA, USA).

2.2. Friction coefficient and deformation

The friction coefficient ($\mu_{Interface}$) was determined for the entire push-in and pull-out process, from the raw axial and radial force data presented in Bishop et al. (2014). The measured axial and radial force components (F_{Axial}, F_{Radial}, respectively) were transformed by $\varphi=3.5°$ (see Fig. 1A) into the coordinate system of the interface, to give the tangential and normal force components, defining the friction coefficient according to Eq. (1), for any instantaneous combination of shear and normal force components (F_{Shear}, F_{Normal}, respectively):

$$\mu_{Interface} = \frac{F_{Shear}}{F_{Normal}} = \frac{-F_{Radial}\sin(\varphi) + F_{Axial}\cos(\varphi)}{+F_{Radial}\cos(\varphi) + F_{Axial}\sin(\varphi)} \quad (1)$$

Friction coefficients were determined as functions of radial displacement, and of normal stress for push-in and pull-out. Only data for the maximum applied interference of 900 µm were analysed with relation to normal stress, since they include the full range of stresses applied. Quadratic regression functions were applied to the push-in and pull-out data separately to relate friction coefficients to applied interference and radial stress.

Table 1
Properties of the implant surfaces (Bishop et al., 2014).

Surface	R_a (µm)	Porosity (%)
Polished	0.11	0
Beaded	32.60	45
Flaked	133.00	63

The effective interference is defined as the nominal interference reduced by the permanent radial deformation of the tested bone surface due to the push-in – pull-out cycle. The relation between effective interferences and the nominal radial interference was analysed by linear best fit functions for each surface type.

3. Results

3.1. Friction coefficients

Friction coefficients were highest for the Flaked surface and lowest for the polished surface (Fig. 2), with highest mean friction coefficients of 0.16 ± 0.05, 0.86 ± 0.02 and 1.08 ± 0.04 for Polished, Beaded and Flaked surfaces, respectively. Friction coefficients tended to increase with axial displacement during implantation (Fig. 2A, black lines). Similarly, friction coefficients decreased with decreasing displacement during pull-out (Fig. 2A, red lines). For the porous surfaces mean friction coefficients were lower during pull-out than during push-in, with the Flaked surface experiencing a very high rate of change in friction coefficient at the highest interference. Friction coefficients for both porous coatings tended towards a more linear variation with displacement at the lower interferences, with more similar magnitudes.

Similar trends were observed for the variation of the friction coefficient with normal stress (Fig. 2B). Friction coefficient magnitudes for push-in increased with normal stress initially, then levelled off and decreased for the Flaked surface at higher normal stresses (> 3 MPa). The pattern was similar for pull-out but friction coefficients were higher than those for push-in for Polished and Beaded surfaces. Coefficients of regression are provided in Table 2.

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