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A biomechanical testing system to determine micromotion between hip implant and femur accounting for deformation of the hip implant: Assessment of the influence of rigid body assumptions on micromotions measurements

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ABSTRACT

Background: Accurate pre-clinical evaluation of the initial stability of new cementless hip stems using in vitro micromotion measurements is an important step in the design process to assess the new stem's potential. Several measuring systems, linear variable displacement transducer-based and other, require assuming bone or implant to be rigid to obtain micromotion values or to calculate derived quantities such as relative implant tilting.
Methods: An alternative linear variable displacement transducer-based measuring system not requiring a rigid body assumption was developed in this study. The system combined advantages of local unidirectional and frame–and–bracket micromotion measuring concepts. The influence and possible errors that would be made by adopting a rigid body assumption were quantified. Furthermore, as the system allowed emulating local unidirectional and frame–and–bracket systems, the influence of adopting rigid body assumptions were also analyzed for both concepts. Synthetic and embalmed bone models were tested in combination with primary and revision implants. Single-legged stance phase loading was applied to the implant – bone constructs.
Findings: Adopting a rigid body assumption resulted in an overestimation of mediolateral micromotion of up to 49.7 μm at more distal measuring locations. Maximal average relative rotational motion was overestimated by 0.12° around the anteroposterior axis. Frontal and sagittal tilting calculations based on a unidirectional measuring concept underestimated the true tilting by an order of magnitude.
Interpretation: Non-rigid behavior is a factor that should not be dismissed in micromotion stability evaluations of primary and revision femoral implants.

1. Introduction

Worldwide, approximately one million patients undergo total hip arthroplasty (THA) surgery each year. THA is considered an accomplished surgical procedure, but despite survival rates of 92% to 97% (Britton et al., 1996) at 10 year follow-up, a large number of revision operations are needed every year.

The initial per-operative stability of the stem in the femoral bone has an important influence on its long-term fixation, especially in cementless primary and revision THA (Viceconti et al., 2006a; Viceconti et al. 2006b). Initial stability is determined by the amount of non-permanent, recoverable, relative motion at the bone-implant interface, referred to as micromotion. Micromotion is associated with the elasticity of the implant – bone construct (Gheduzzi and Miles, 2007). Micromotion should not exceed 150 μm in order to ensure long term stability through osseointegration (Pilliar et al., 1986; Jasty et al., 1997). Therefore, accurate pre-clinical evaluation of the initial stability by means of micromotion measurements is an important step in the design process of new cementless THA implants.

In vitro evaluation of the initial stability of THA implants through micromotion measurements has been performed in numerous studies. The majority of systems use some combinations of linear variable displacement transducers (LVDTs) (Østbyhaug et al., 2010) to measure micromotion. Nevertheless a variety of alternative measuring methods have been reported including: optoelectronics (Buhler et al., 1997a, 1997b; Speirs et al., 2000), radiographs (Berzins et al., 1993), dial gauges (Jamali et al., 2006), differential variable reluctance transducers

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(DVRTs) (Bachus et al., 1999), radiostereography (RSA) (Tarala et al., 2011), microCT measurements (Gortchacow et al., 2011) and 3D video analysis systems (Westphal et al., 2006).

LVDT – based measuring systems can roughly be categorized into two concepts: local unidirectional and frame–and–bracket systems (Gheduzzi and Miles, 2007). Unidirectional systems (Bieger et al., 2012; Claes et al., 2000; Cristofolini et al., 2007) fix a bone reference for the single degree of freedom transducer (a LVDT in the majority of cases) as closely as possible to the implant measuring location. Implant motion is then measured by connecting the LVDT to a transcortical pin attached to the implant, thus measuring the relative motion between the pin and the LVDT anchorage. Most unidirectional systems limit the measurement to one predefined direction per measuring location, but do allow simultaneous measurement at multiple measuring locations to monitor a region of interest using a cluster of single degree of freedom transducers. Rotational information is not readily available, although relative tilting of the implant in the frontal and sagittal plane has been derived based on a set of unidirectional measurements and trigoniometric analysis assuming both bone and implant can be considered rigid bodies (Bieger et al., 2012, Claes et al., 2000; Gotze et al., 2002).

Alternatively, several studies use a frame – and-bracket system (Britton et al., 2003; Britton and Prendergast, 2005; Chareancholvanich et al., 2002; Enoksen et al., 2014; Fottner et al., 2011; Liu et al., 2003; Maher et al., 2001; Maher and Prendergast, 2002; Østbyhaug et al., 2010; Park et al., 2010). The bracket typically supports a number of target spheres that are rigidly attached to the implant stem whose movement is monitored by a set of LVDTs fixed to a frame that is attached to the bone (or vice versa). The advantage of these systems is that all six degrees of freedom can be measured in one region of interest. However, a disadvantage is that this technique effectively measures the relative displacement between the point of attachment of the frame to the bone (or implant) and the point of attachment of the bracket to the implant (or bone) and thus may not provide a true estimate of the local micromotion (Gheduzzi et al., 2007). Systems using a configuration where the measuring frame is attached to the implant and the bracket locally to the bone at different measuring levels consider the implant to be rigid in order to calculate micromotions (Østbyhaug et al., 2010; Wik et al., 2011; Enoksen et al., 2014).

Recently developed non-LVDT based micromotion measuring methods also adopt a rigid body assumption for the implant (Gortchacow et al., 2011).

This study presents an alternative LVDT-based measuring system developed to combine some advantages and best practices of unidirectional and frame-and-bracket concepts. No rigid body assumptions for bone or implant were required. The system allowed measuring bone and implant motion simultaneously with respect to a common reference frame attached to the implant. Additionally, both a unidirectional as well as a frame-and-bracket measuring concept can be emulated with the system allowing analysis of the influence of adopting rigid body assumptions for both concepts. Possible errors on the micromotion estimates or derived quantities were determined. This assessment was carried out for primary and revision THA implants in combination with synthetic and embalmed bone models.

2. Methods

2.1. Bone specimens and implants preparation

Primary and revision implants were tested using synthetic composite femurs (Sawbones model 3403 (size medium), Sawbones Europe AB, Malmö, Sweden). In order to assess the influence of the bone model on the results, an additional seven embalmed human cadaveric femurs were tested in combination with the primary implants.

An uncemented Wright Profemur L modular stem (Wright Medical Technology, Inc., Memphis, TN, United States) (Fig. 1A) was used for primary implant. A size 5 was selected for the synthetic femur; sizes 5, 6 and 7 were selected by the surgeon for use in combination with the embalmed femurs. The Profemur L is a wedged-shape, proximal fit-and-fill implant made of Ti6Al4V titanium alloy. The revision implant was an uncemented Wright Profemur R modular revision stem (Fig. 1B). A proximal plasma sprayed body (size small) was combined with a 135 mm straight stem, both of which are made of Ti6Al4V titanium alloy. A short 30 mm varus/valgus neck (Wright PHA01252) and a ceramic 32 mm head were used for all implants during testing.

An attachment site to accommodate and align the measuring frame was machined at the shoulder of all implants. Using the measuring frame as reference in combination with a set of guidance bushings, threaded holes (diameter 3 mm) were machined at all measuring locations to secure the implant pins during testing. Drilling the implant holes before implantation avoided excessive loading and possible damage to the bone-implant interface due to drilling action once implanted (Abdul-Kadir et al., 2008).

All bone models were prepared by the same experienced surgeon following standard surgical procedure while using manufacturer provided broaches and reamers. The implants were forcefully inserted until an adequate press – fit was achieved. Subsequently, the measuring frame was again attached to the implant to serve as a drill guide for four bone holes (diameter 8 mm (Choi et al., 2010)) to accommodate the bone bushings. This ensured bone and implant measuring locations aligned precisely. The femurs were then secured in plastic cylindrical pots with 2 component fiberglass putty (Motip Dupli, Temse, Belgium) at the distal condyles. The bones were aligned with their anatomical axis parallel to the cylinder central axis in a custom mounting stand while the putty cured.

2.2. Micromotion measuring system

Micromotion was measured in two transverse planes corresponding proximally to the lesser trochanter and distally to 40 mm inferior (Fig. 2). Linear displacement sensors were secured to the measuring frame at two locations per transverse plane (one location in the frontal plane and one location in the sagittal plane) to track the movement of a 8-mm tube, or bushing, screwed into the bone, and a complementary 3-mm steel pin screwed concentrically into the implant through the bushing hole in the bone (Fig. 3). Alignment between bushing and pin was ensured by a guiding system that was mounted on the measuring frame. Two types of linear displacement sensors were used; LVDTs with a resolution of 1 μm (GSHM-2.5B, Singer Instruments, Tirat Carmel, Israel) and DVRTs with a resolution of 300 nm (MG-DVRT, AE Sensors, Dordrecht, The Netherlands). The compact design of the measuring system allows simultaneous measurements at different measuring levels, with respect to the same measuring frame and reference system.

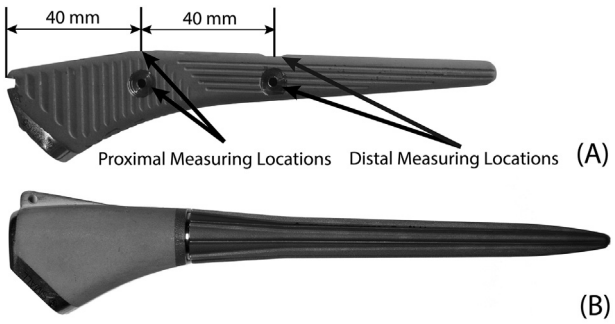

Fig. 1. A depiction of the Profemur L primary implant (A) and Profemur R revision implant (B) used in this study. The Profemur R is shown before adaption; the Profemur L is shown after adaptation with the proximal slot and the proximal and distal threaded holes to mount the implant pins clearly visible.