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A vibrational technique for diagnosing loosened total hip endoprostheses: An experimental sawbone study

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ABSTRACT

Aseptic loosening of hip implants is a severe orthopaedic problem and a valid diagnosis is often difficult. A potential method to determine loosening of the prosthesis is a swing analysis of the bone-implant interface using a vibrational technique. In this study, hip models were constructed to assess the vibration behaviour of the stem and cup components. Four different states of implant loosening were simulated: (1) stem and cup stable, (2) stem loosened and cup stable, (3) stem and cup loosened, and (4) stem stable and cup loosened. The model was excited at the lateral condyle of the femur between 100 Hz and 2000 Hz. Resonance spectra were recorded using an optical laser vibrometer and an accelerometer-based system. Analysis of the spectra revealed shifts of the resonances towards lower frequencies, especially in the case of a loosened stem component. The integral value of the spectra was a second parameter that was sensitive to a stem loosening. In the case of a loosened cup, a peak count analysis resulted in a significantly higher number of counts. In our model, different states of implant loosening could be determined with a vibrational technique and the localisation of the loosened component could be distinguished as well.

1. Introduction

Total hip arthroplasty is one of the most successful operations in modern medicine. More than one million of implantations take place worldwide each year [1–3]. Despite considerable progress in this field in recent years, a large number of revisions still take place. The 10-year survival rate in Sweden is currently 95%. By far the most frequent indication for a revision surgery is aseptic loosening. A rate of 71.2% is registered in the Swedish hip register [4]. Löhr and Katzer [5] reported a rate of up to 90%. The cup component is affected conspicuously more often than the stem [6].

However, conventional methods, such as the analysis of plain film radiography, arthrography and scintigraphy, exhibit shortcomings in the detection of loosened implants in terms of sensitivity and sensibility [6–9]. Consequently about 10% of revisions prove unnecessary [10]. The detection of a loosened cup component is particularly difficult.

Vibrational techniques have been successfully applied in biomechanical and medical research. For example, these have been used to assess the mechanical properties [11–13] of long bones, to quantify fracture healing [14–17] and to monitor the osseointegration and stability of dental [18–20] or endoprosthetic implants [21]. Various research groups are working on vibrational techniques as a diagnostic tool to detect implant loosening in endoprosthetic implants. Several studies are using set-ups based on accelerometers and focus mostly on the detection of just a loosened stem [7,8,22,23]. Some clinical in vivo studies have been performed [6,8,24,25]. Qi et al. [26] and Pastrav et al. [27] published studies using the finite element method to simulate different boundary conditions of stem implants and to analyse the effect on the resonance frequencies. A few groups have published studies with alternative measurement methods. Puers et al. [28] and Clasbrummel et al. [10] reported telemetric attempts with integrated sensors in the prosthesis. Rowlands et al. [9] used ultrasound and the Doppler effect. Dahl et al. [29] transferred this method to the ankle. Ruther et al. [30] reported an acousto-mechanical approach with modified stem. However, little has been published about loosened stems in combination with fixed or loosened cup components and the detection of cup loosening, in particular, is far from adequate.

The aim of this explorative study was to assess the vibrational behaviour of a complete total hip endoprosthesis (stem and cup) in a sawbone model. This model was chosen to determine characteristic parameters of a loosened implant under standardised conditions. Our main research question was whether clear differences are detectable in the resonance structure of the joint between

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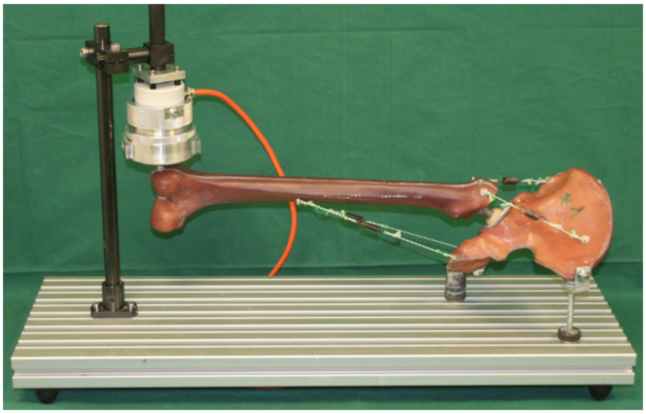

Fig. 1. The sawbone model as test set-up for a vibrational analysis of the implant stability.

stable and loosened implants. A second question is whether a loosened implant causes non-linearities in the joint which appear as additional peaks in the measured spectra. Then based on this data is it possible to distinguish different localisations of loosening and, in particular, the detection of a loosened cup component? Two different excitation methods were compared: excitation at the lateral condyle and excitation at the crest of the ilium.

2. Materials and methods

2.1. Sawbone model

We used a sawbone model (Fig. 1) that consisted of a femoral bone and a hip bone of fourth-generation composite sawbones (Sawbones Europe AB, Malmö, Sweden). Six pairs were prepared for the study ($n = 6$). In the femoral bones, the CLS^{TM} Spotorno^{TM} stem (size 10, Zimmer, Inc., Warsaw, IN, USA) was implanted. To ensure a standardised seating of the implant, the stem was subsequently forced in with up to 4 kN, according to the protocol of Thomsen et al. [31]. Allofit^{TM} Cups (Ø52 mm, Zimmer, Inc., Warsaw, IN, USA) were implanted in the hip bones. A ceramic head with a diameter of 28 mm was used together with the corresponding polyethylene inlay.

The hip bone was attached to a test bench. It was fixated at the location of the pubic symphysis and close to the auricular facies. Therefore the hip bones were prepared at each location with a 20 mm M8 threaded rod. They were screwed into the hip bone halfway. A rubber damper was placed between the test bench and the pubic symphysis to simulate the cartilaginous and flexible connection between two hip bones. For further installations thread inserts were applied (Ensat®-SK M 4, 302 100 040.160, Kerb-Konus-Vertriebs-GmbH, Amberg, Germany). Four tension springs were used to assemble the femora and hip bone to stabilise the artificial joint. Two springs (spring rate = 4.17 N/mm) ran along the gluteus medius muscle and two springs (spring rate = 2.26 N/mm) ran along the adductors magnus and longus. The springs were fixated at the bones with cords (polyamide, Ø1.3 mm, tensile strength = 50 daN). By using the same springs in all different test-setups, we achieved a consistent load situation in the joint.

Four different fixation modes of the implants were assessed in this study:

1. Stem and cup were stable and rigidly fixed in the host sawbone (abbreviation: st-st; reference state).
2. Stem was loosened and cup was stable (lo-st).
3. Stem and cup were loosened (lo-lo).
4. Stem was stable and cup was loosened (st-lo).

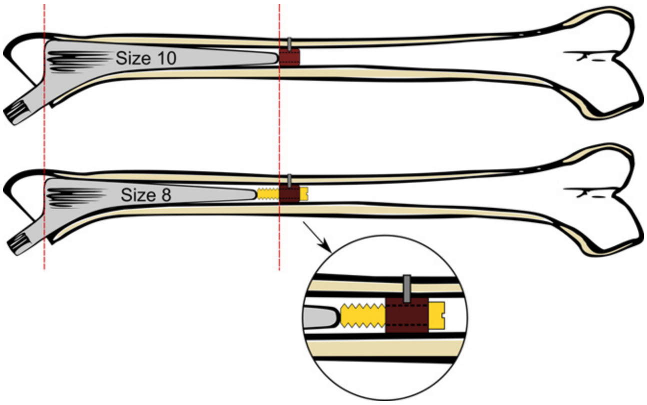

Fig. 2. Preparation of the sawbones to simulate a loosened stem implant: the distal tip of the well-fixated stem was marked as reference with a polyamide plug (A). To simulate loosening, the stem was replaced by a smaller one. To compensate for the length variation, a screw was turned into the plug (B).

These four loosening situations have been successively simulated with each of the six prepared bone pairs. To realise the loosened states, the femora were prepared with a polyamide plug with internal M 12 thread (Fig. 2A). The plug was inserted after implantation through the emulated medullary canal of the sawbone so that it was in direct contact with the distal tip of the stem. To prevent displacement of the plug, it was fixated with a locking pin. To simulate a loosened situation, the stem was replaced by a size 8 stem with slightly smaller geometrical dimensions (mass difference = 27 g). To compensate the difference in length between these two implants (10 mm) and to avoid the stem subsiding until it was stable, an M 12 polyamide screw was turned into the plug in the loosened state (Fig. 2B). A loosened acetabular component was simulated by substituting the implant by a cup with abraded exterior side to avoid any mechanical anchorage between implant and bone bed (mass difference = 10 g).

2.2. Actuating element

The bone-implant-compound was excited mechanically with an electromagnetic shaker system (TV 50009, TIRA GmbH, Schalkau, Germany). Considering the envisaged practice of the patient, the location of excitation is already constricted by the distribution of the soft tissue around the involved bones of the hip joint. There are two locations predestined for excitation: the lateral condyle as well as the crest of the ilium. Both are well palpable.

The point of excitation was either the lateral knee condyle or the crest of the ilium. In the second case, the femur was also supported at the medial condyle with a hinged bracket.

The shaker was positioned such that a small gap remained between oscillating mass of the shaker and fixation point of the bone. This allowed the oscillating mass to be attached to the bone without force using two-component adhesive X60 (Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany).

2.3. Laser vibrometry

The laser vibrometry (LV) is an optical and accurate, non-contact method for determining vibrations at surfaces. It is the standard industrial technique for highly precise vibrational testing. The system was used as reference measurement and for interpreting the resonance spectra. The six femur–pelvis pairs were scanned in each of the four loosening situations by a laser-scanning vibrometer PSV-400 (Polytec GmbH, Waldbronn, Germany). Accelerations were measured at 78 sample points, spread over the model. Occasionally some points were not optically accessible and therefore