Design and Evaluation of a Device for Measuring 3D-Micromotions of Press-Fit Femoral Stem Prostheses

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INTRODUCTION

Primary stability of uncemented total hip replacements is regarded as a major factor necessary for good quality bony ongrowth to the prosthetic femoral stem and therefore for a successful long-term outcome [1,2]. The remodelling of the endosteal bone in contact with the implant is affected by the relative micromotions of the bone-implant interface and the stress state in the femoral bone. As a result, for optimal biological fixation, translational movements (i.e. primary stability) are of greatest interest. These interface-micromotions generally occur in all three spatial directions. Under physiologic loading, they consist of a cyclic amplitude and change in the mean, which in the cranio-caudal direction represents subsidence of the prosthesis.

Existing measurement strategies which are based on dial gauges, extensometers, LVDT's, hall effect transducers or strain gauge techniques provide information about only one component of the general three-dimensional micromovement [3,4,5]. Furthermore, fixation of sensors away from the point of interface motion measurement, as seen in various studies [4,5], may result in the registration of motions due to elastic deformation of the femoral or prosthetic shaft in addition to the interface motion.

The objective of this study was to develop, validate, and apply a new technique which allows the *precise measurement of the isolated 3D interface motion* at three different points along the femoral shaft.

Figure 1: Conceptual Design of the Sensor

MATERIALS AND METHODS

The present measuring technique is based on a sensor combining optoelectronic with precision mechanical components. Spherical measuring tips of three sensors were placed on the prosthesis at predefined locations: the distal tip of the prosthesis and at the middle and proximal third of the femoral stem. The sensors were mounted on an adapter unit which was anchored in a transverse 9 mm hole drilled in the cortex. Precision, play-free, ball bearing mechanisms allowed transition of the detected motion to a infrared emitting diode on the opposite end of the sensor (Fig. 1). Photons emitted by this LED were registered by a two dimensional silicon position sensitive detector (PSD). The XY-movements of the LED were measured directly by the PSD. Micromovement of the prosthesis in the Z-axis of the transducer brings the LED closer or farther to the photodiode, thereby increasing or decreasing the intensity of the light beam on the PSD. Since the two-dimensional position sensitive detector generates photocurrents, which sum is proportional to the intensity, the highly non-linear correlation between LED-PSD distance and light intensity was used to acquire the third dimension at the same time as measuring the XY-motions. Due to the thermal response of the PSD, a ntc-resistor was also integrated to exclude thermodriffs during long-term testing.

Static and dynamic validation indicated that the maximum system error was ± 4.9 microns within a measuring range of ± 0.75 mm in each spatial orientation.

To demonstrate the utility of the sensors in interface motion measurement, an *in-vitro* experiment was performed. Seven paired fresh cadaveric femora were used for testing two different types of uncemented femoral stems: CLS stem (Spotorno) and Cone prosthesis (Wagner) both from Protek AG, Switzerland. Using a custom loading rig the femora were subjected to sinusoidal cyclic loading in a bi-axial materials testing machine. A cranio-caudal force F_{cc} with a frequency of 1 Hz was combined with a 0.5 Hz antero-posterior force F_{ap} having a magnitude of 10% of F_{cc} . Loading steps of 1-, 2- and 3-times body weight (BW) were applied. Custom software allowed for real-time graphical display of the applied forces and the detected movements.

RESULTS

The postprocessing software allowed the analysis of: (A) *Three-dimensional motion* displayed in cylindrical coordinates (Fig. 2); (B) *Motion amplitude (MA)*, which is the difference of the measured minimum and maximum

value for one loading cycle and (C) *Total motion* (TM), which is the time-based average micromotion of one loading cycle (Fig. 3).

(A) *Three-Dimensional Motion*: A typical 3D interface motion behavior for one loading cycle (loading step 3: $F_{cc}=2.07$ kN; $F_{ap}=207$ N) is illustrated for both types of prostheses in Fig. 2. The midshaft of both prostheses was the point with the least motion in all directions. At the distal tip the Cone prosthesis also showed very little movement. A comparably large MA was measured at the proximal position for both prostheses. This motion loop was mainly oriented in the X'Z'-plane (=frontal, see figure 1).