Development of a testing method for the determination of interfacial micromotions of short-stemmed hip endoprosthesis


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Abstract

Short stemmed hip endoprostheses represent a relevant alternative to standard sized total hip stems. Especially in terms of bone stock preservation and minimal invasiveness the reduced length of such implants is beneficial. However, the smaller implant size is linked to a reduced surface geometry and thereby bone-implant-interface to provide implant stability. In order to evaluate the interfacial micromotions of a short stem implant experimentally a new measurement device was developed and validated with an optical system.

1 Introduction

Although at long-term follow-up conventional femoral stems perform exceedingly well in primary total hip replacement (THR) some limitations persist [1, 2, 3]. Proximal-distal mismatch, non-ideal load transfer, loss of bone, and difficulties with minimally invasive surgery may compromise a successful outcome. As successful THR requires stable initial and long-term axial and rotational fixation metaphyseal-engaging short-stem implants have been designed as an alternative to address these issues especially in younger patients. They are one possible solution to the challenges in achieving stable fixation in varying proximal femoral morphology and optimizing proximal load transfer, while providing dependable fixation.

To achieve biomechanical settings as close as possible to the normal hip there currently exist two concepts to restore the femoral off-set with short stems.

Similar to modern standard total hip stems a variable curvature of the short stem and different off-set adapters are used. On the other hand the resection level of the femoral neck and a varus or valgus alignment of the short stem allow for femoral off-set restoration.

However, with regard to the short fixation section an appropriate implant size is mandatory to avoid subsiding and gain a sufficient press fit for primary stability [4]. One goal of femoral prostheses is the transfer of loads on the proximal femoral bone stock and short stems seem to accomplish this task.

From a biomechanical point of view a as far as possible proximal implant fixation reduces the risk of stress shielding.

Depending on the design features short stemmed prostheses follow three different concepts:

- Intramedullary fixation with or without contact to the lateral corticalis of the proximal femur and extramedullary fixation. Latter, such as e.g. the thrust plate prosthesis has been given up [5].

The disadvantage of intramedullary fixation with contact to the lateral corticalis is an influence on femoral bending which supports stress shielding. But primary stability is higher with this concept.

Minimal invasive surgery in total hip arthroplasty facilitating less invasive surgical approaches provides reduced derogation of bone and soft tissue, and a favorable revision setting. Therefore, short stemmed endoprostheses represent a relevant alternative in this context. But this relatively new concept remains to be proven by long-term clinical follow-up investigations.

In order to evaluate primary stability of THR systems and thereby to estimate their possible clinical outcome experimental tests and numerical analysis has been performed in the past, especially in the pre-clinical period of new endoprosthetic implants. This estimation is based on the widely accepted consensus that initial implant stability is necessary for the formation of secondary stability [6].

While in-vitro measurement of interfacial micromotions of standard sized primary THR implants has been reported in the past, investigations of short stemmed implants are rare [7, 8, 9]. Due to the reduced implant surface the influence of measurement attachments is more pronounced compared to standard implants.

2 Methods

In order to measure the interfacial micromotions between implant and bone a mechanical device based on previous work [10] was adapted for the special situation of short stemmed implants.

A metal frame was designed to fix four linear variable differential transformers (LVDT) (DP5S, Solartron Metrology, Meerbuch, Germany). Three were positioned orthogonal and two parallel to each other, to measure three translational and one rotational displacement (see Figure 1). In order to keep the influence onto the bone-implant-system as small as possible the motions of the implant were trans-
ferred exterior to the bone by a pin, which passes through a small hole in the cortical bone. The pin is fixed tightly into the stem implant and ends outside of the bone in a measuring block with orthogonal surfaces. All four LVDT’s, rigidly attached to the cortical bone, contact to the measuring block and thereby indicate the relative motions in the bone-implant-interface.

3 Results

Comparison between optical and mechanical measurement system showed a good correlation, as shown in Image 2. The general accuracy of the stereoscopic system with the used lenses and camera frame is in the range of 0.01 mm in a measuring volume of 300x300x300 mm. This is clearly visible as a noisy signal for the optical system in Image 3. However, the space which can be used for micromotion measurements is larger compared to the measuring range of the LDVT’s, which comprises a measurement space of 5x5x5 mm with the used sensor types. Within this space the mechanical measurement system provides a resolution of less than 0.05 µm and an accuracy of 0.05 % of the readout.

Image 1 Micromotion measurement device based on four LVDT’s to measure three translational and one rotational relative motions

LVDT values and synchronized load data from a servo-hydraulic testing machine is collected by a LabView program (National Instruments, Munich, Germany) with a frequency up to 20 Hz and stored to file for later analysis.

Image 2 Graphical user interface for the LVDT based measurement device

A custom-made graphical user interface, as shown in Figure 2, was generated to provide information about current LVDT values in comparison to the available measurement range of the used sensors. In order to evaluate the accuracy of the measuring device, experiments were conducted in conjunction with a stereoscopic measuring system (Pontos, GOM, Braunschweig, Germany) at the maximum frame rate of 15 fps. Test specimens for this comparison were loaded by a servo-hydraulic testing machine (Instron 8874, Pfungstadt, Germany) with a sinusoidal load at 1 Hz. According to the Nyquist-Shannon sampling theorem both measuring techniques were fast enough for the applied load frequency.

Image 3 Comparison between optically and mechanically determined interfacial micromotions

4 Conclusion

The developed mechanical measuring device based on LDVT’s is capable to measure interfacial micromotions between implant and bone with an accuracy smaller than the anticipated relative motions during dynamic implant loading. Neither the mechanical nor the optical measuring methods used show superior properties or unique characteristics to qualify the technique as the best. While the mechanical system offers the best accuracy, it is associated with a limited measurement length/space. This may constrain the testing proceedure, especially in case of implant migration. Otherwise the measuring device needs to be relocated to continue the test; additionally the resulting coordinate frame is changed. On the other hand, the amount of data which is recorded during one experiment and needs to be analyzed is relatively small compared to the picture information of the optical system. The same issue arises looking at the maximum test duration. All LVDT data is stored in a LabView container file which is restricted by available hard disk space and operating system limitation only. Stereoscopic data, of the system used, is stored as twin 5M (2448x2050 px) grayscale images per frame at a maximum rate of 15 fps. At the moment only random access memory...
(RAM) and fast solid state disks (SSD) can handle such a data stream. This limits the measurement duration to the available RAM size of the used computer system (e.g. 36 GB of RAM can handle approx. 900 twin-frames, or 60 s at 15 Hz), because SSD’s are currently not supported by the system. This compromises the use of the optical system to short or non-continuous measurements (as shown in Image 3).

Additionally, all the experimental data need to be processed and stored for later evaluation. While the LDVT data, stored in plain text files, stays in the range of megabytes the optical system quickly need gigabytes with all the problem of processing, storing and general handling. Opposing the hardware and data limitation, the optical method offers some advantages compared to the mechanical system. Due to the fact, that all information's are stored in images and processed after the experiment when time is uncritical the number of measuring points is almost unlimited. Hence, displacement fields could be evaluated by this method, if the test specimens offer visibility to the camera system. Additionally, no forces, such as spring force or inertias of mechanical devices, can falsify the implant-bone system during the experiment.

Based on the reported accuracies and advantages of the mechanical measuring device, verified by the stereoscopic system. Due to the fact, that all information’s are stored in images and processed after the experiment when time is uncritical the number of measuring points is almost unlimited. Hence, displacement fields could be evaluated by this method, if the test specimens offer visibility to the camera system. Additionally, no forces, such as spring force or inertias of mechanical devices, can falsify the implant-bone system during the experiment.

Based on the reported accuracies and advantages of the mechanical measuring device, verified by the stereoscopic system, the LDVT-based device will be used for further primary stability investigations of short-stemmed implants.

5 References


