# NON-INVASIVE CHARACTERIZATION OF TOTAL HIP ARTHROPLASTY BY MEANS OF PASSIVE ACCELERATION MEASUREMENT

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***Abstract- This paper presents a non-invasive measurement method to detect and characterize failures and material imperfections in total joint prostheses based on acceleration measurement. Therefore, a prototype sensor has been developed to fulfill the requirements of a medical-technical sensor. This sensor has been tested on patients with total hip arthroplasty. Special emphasis is put on the real-time processing of measurement data by means of intelligent signal processing as well as reliable and repeatable measurement procedures, including standardized positions for the sensor front-end and a standardized motion-sequence the patient is performing.***

**Index terms*:* Total hip arthroplasty, Non-invasive measurement, Failure characterization, Acceleration measurement, wear detection**

## I. INTRODUCTION

The implantation of a total hip arthroplasty (THA) has become a standard medical operation in the western society. Early limitations, such as fixation in the bone and fatigue of material, were overcome due to permanent enhancements of the material and operating techniques. Today, the

limiting factor of durability of THA is wear caused by friction between head and cup of the artificial hip joint. In a chain reaction, debris from wear particles leads to chronic inflammation, resorption of bone, loosening of the endoprosthesis, and full breakdown of the endoprosthesis, requiring a revision operation and the replacement of the endoprosthesis. It is hence important to be able to diagnose wear of an endoprosthesis in a very early stage to avoid loosening.

Especially for hip endoprostheses, only a small number of approaches to investigate failures, imperfections, and wear are known since the prosthesis is surrounded by comparably large amount of soft tissue. The state of the art methods to detect wear phenomena in endoprostheses are conventional diagnostic imaging techniques such as X-ray, magnetic resonance tomography, or nuclear medicine (isotopes) [1]. All these methods have limited resolution and allow wear detection in a later, more significant stage only.

An experimental method using radioactive marker particles placed on the boundary layers of the endoprosthesis is presented in [2]. When the surface layer of the endoprosthesis is subject of wear, these particles are found in metabolites and wear can be diagnosed. Up to now operative revision is the only way to detect early wear in THA.

A promising, non-invasive technique to investigate and characterize the state of THA is vibration analysis. Mechanical sine wave vibrations are applied to the region of the human body to be examined by means of an electromagnetic shaker. The response signal is acquired using an accelerometer and spectral analysis is then applied to detect loosening effects [1, 3, 4]. Devices and methods have been used that are fabricated as an implantable system (i.e. a sensor system that is directly connected with the endoprosthesis and data is transferred through the tissue by means of radio frequency data transfer) [1].

Different sound types caused by THA, such as knocking, crunching, grating, cracking, squeaking, have been investigated in [5] by means of vibration analysis and fluoroscopic spectroscopy. Certain bearing couples, such as ceramic-on-ceramic, have a strong influence on the sound emission behavior of the endoprosthesis.

## II. SENSOR PRINCIPLE

In preliminary investigations carried out in close cooperation with the Department of Orthopaedics, Medical University Graz, Austria, it could be observed that for certain hip endoprostheses (i.e. for certain bearing couples) an audible sound is emitted when the patient makes a well-defined motion sequence (e.g. climbing the stairs). Depending on the angle of the patient's thigh in an upright position and the stress, squeaking and other sound can be detected. The presence of the sound due to friction between the mechanical components of a prosthesis - regardless if it is audible (i.e. suitable frequency and level of intensity to hear the sound) or not - is an indicator for an imperfection of the endoprosthesis. Determining the angle of the thigh and the load while the sound is emitted allows for characterizing the type of imperfection and the location on the endoprosthesis.

The sensor principle hence comprises the mounting of acceleration sensors directly on the patient's skin. Since solid-borne sound can be reliably detected close to the surface of the femur, certain "standardized" points to place the acceleration sensors are preferred. Fig. 1 shows possible positions to determine solid-borne sound originating from THA.

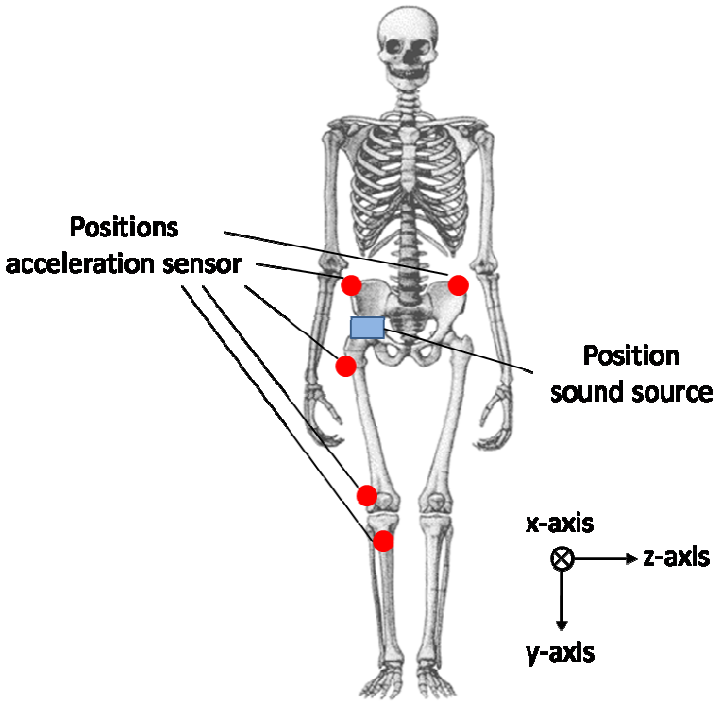



Fig. 1: Positions to place the acceleration sensors to determine solid-borne sound originating from total hip arthroplasty. The position of the sound source is the imperfect endoprosthesis

To standardize the motion sequence for the patient and to determine the trend of the load/stress in the hip endoprosthesis, a podium has been equipped with a load cell. The patient steps onto the podium, remains there for a given time and then steps back down onto the floor. This procedure is repeated while the load cell signal as well as the acceleration sensor data are recorded.

## III. SENSOR FRONT-END AND TEST SETUP

A sensor to be used in medical application requires high standards in terms of safety and reliable operation. A laboratory prototype comprising a fully functional hip endoprosthesis, which is connecting two pieces of wood, has been used to test several acceleration sensors. This laboratory setup is used to find out, which of the acceleration sensors features sufficient accuracy and sensitivity. For the final sensor design, three MEMS-based accelerometers of type LIS2L02AL from ST Microelectronics are used. This sensor type is an analog accelerometer with two orthogonal sensitive axes. Acceleration is determined by means of two capacitive half-bridges. Therefore, it is possible to obtain both the oscillation caused by the endoprosthesis and also the position of the sensor with reference to the gravity field with the same sensor. The actual angle between the thigh and the vertical direction can hence be derived by means of signal processing. The sensor can be operated in a range between –2 g and +2 g and has a minimal resonance frequency of 2 kHz. One of the main advantages for the use in a medical application are the small dimensions (5 mm x 5 mm x 1.6 mm). The sensor front-end is fully sealed in synthetic resin to avoid any contact between the patient and an electrically conductive part.

All further functional components of the sensor system including signal conditioning, analog to digital conversion, digital filtering, isolation, and communication have been designed and developed at the Virtual Vehicle Competence Center. The block diagram in Fig. 2 shows the main functional components of the sensor system.

To ensure a reliable reference and enable to calibrate the three acceleration sensors once they are fixed at the patient at the positions shown in Fig. 1, a vibration motor is used. The patient stands still and hence the endoprosthesis does not emit sound. The motor is operated at a frequency of 9.000 rpm (i.e. 150 Hz) and excites a solid-borne sound when pressed against the patient’s hip. This sound signal (acceleration) is acquired at the three sensor front-ends and their readout is observed on the control desktop on the PC using the software tool LabView 2009 from National

Instruments. Time-critical routines were implemented in Microsoft Visual C++ 2008 Express Edition and have been included as Dynamic Linked Library (DLL) in LabView. Amplification for the signal conditioning block can be adjusted and the positions of the sensors and their physical contact can be checked with real-time impact analysis.

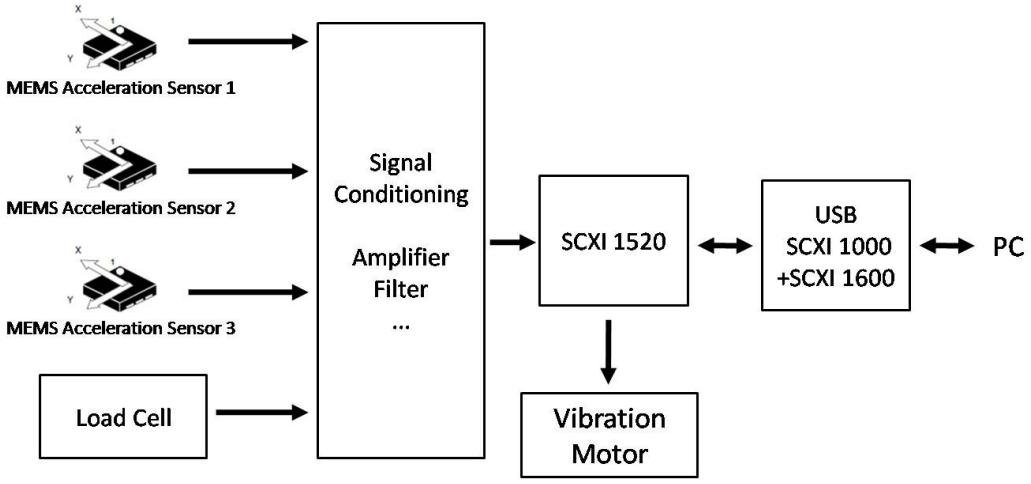



Fig. 2: Block diagram of the functional components of the sensor system and communication to the PC/Data Acquisition Card

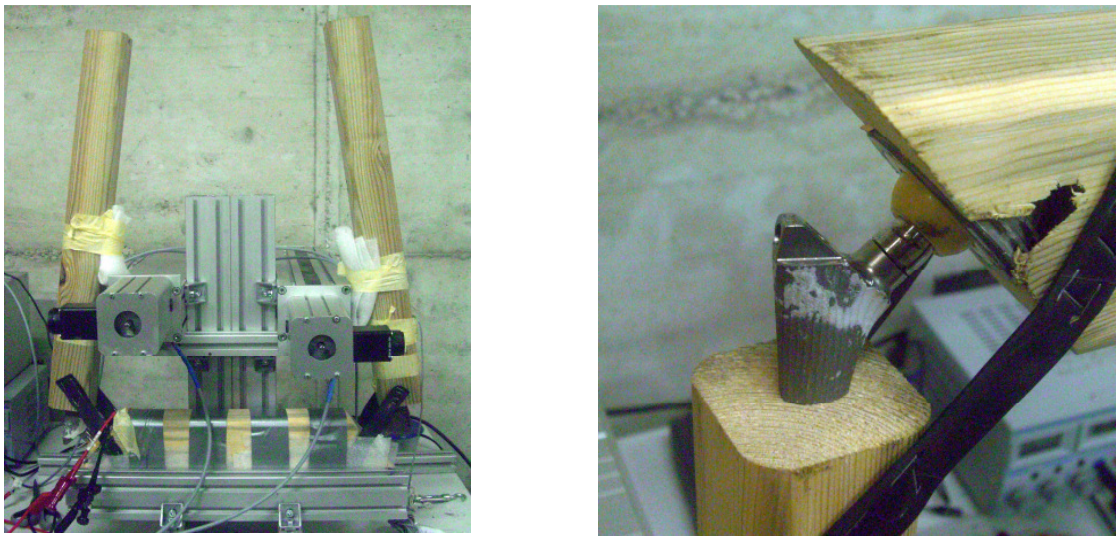
A low pass filter ($f_g$=2 kHz) and an impedance converter to allow for measurement with low-impedance input are included in the measurement PCB board. Due to the small amplitude of the load cell in the podium, an instrumentation amplifier with fixed amplification is used.
Data acquisition is done using an SCXI 1000 DAQ system from National Instruments with the modules SCXI 1520 and SCXI 1600. Sampling rate has been chosen to be 25 kHz.

## IV. MEASUEMENT RESULTS

a) Measurement Results - Laboratory Test Setup

To test the sensor under realistic but highly reproducible conditions, a laboratory setup has been designed. Two pieces of wood are mounted on either end of a ceramic-on-ceramic hip prosthesis with well known imperfection so that one piece of wood represents the femur and the other the

hip of a patient. The laboratory setup allows investigating the influence of different parameters such as variation of load (i.e. different weight on the endoprosthesis) or the adding of fine ceramic and metal particles in-between the two components of the endoprosthesis (i.e. to simulate wear). Fig. 3 shows the laboratory test setup with the ceramic-on-ceramic hip prosthesis.



(a) (b)

Fig. 3: Laboratory test setup to investigate a ceramic-on-ceramic hip prosthesis (a): Setup prepared to be operated under a certain load and (b): Detail photo of the hip prosthesis.

With this laboratory test setup various experiments have been conducted, testing the impact of load as well as the impact of wear onto the recorded acceleration.

Fig. 4 shows the time signal of the LIS2L02AL acceleration sensor under a load of 30 kg (i.e. a weight of 30 kg has been placed on the vertical “femur” of the setup shown in Fig. 3a. While the “hip” was kept stationary, the “femur” was moved using a pecking motor.

Fig. 5 shows the frequency spectrum of this signal, indicating that major frequency components between 200 Hz and 300 Hz can be found in the signal.

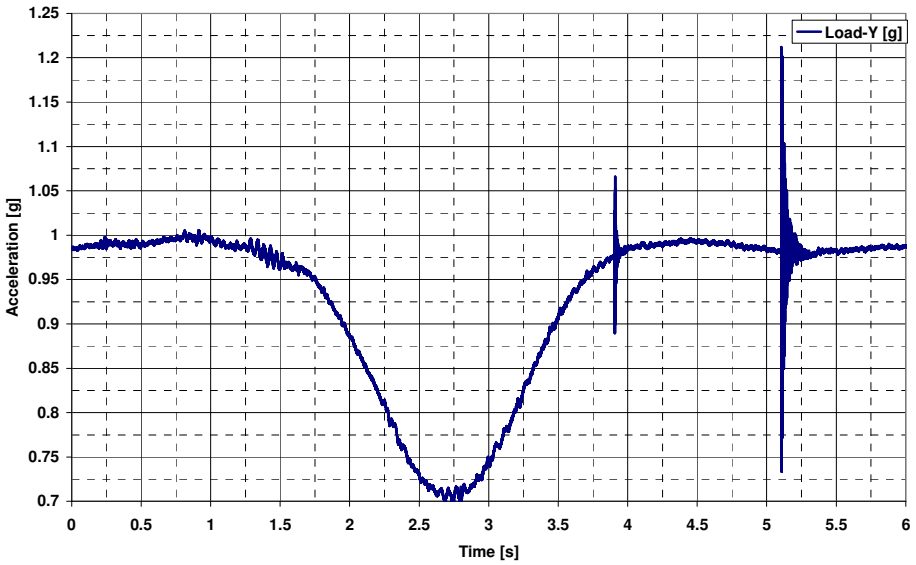



Fig. 4: Time signal of the recorded acceleration caused by a a ceramic-on-ceramic hip prosthesis under a load of 30 kg.

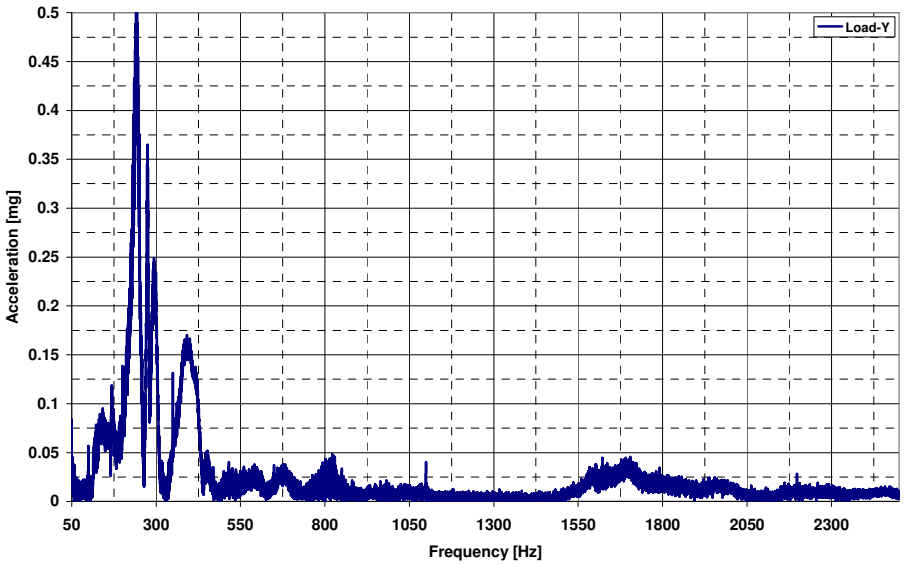



Fig. 5: Frequency spectrum of the recorded acceleration caused by a ceramic-on-ceramic hip prosthesis under a load of 30 kg.

The method of principal component analysis (PCA) has been chosen to evaluate and analyze measurement results obtained in experiments with the laboratory setup. The PCA is a frequently applied method to classify data and can be found in various applications and publications [6, 7].

An $m$ x $n$ data matrix $X$ is split into sub-matrices $M_i$, i=1 ... $n$, with $M_1$ containing the most information, $M_2$ containing the second most information and $M_n$ as the sub-matrix with the least information. To fully characterize the measurement data, all $m$ sub matrices are required. It can be assumed that all sub-matrices with an index p and higher will only contain noise (i.e. data without an evaluable contribution). In most cases, the consideration of two sub-matrices, $M_1$ and $M_2$, is sufficient to describe the most important properties of the data matrix.
Each sub-matrix $M_i$ can be given as the product of two vectors

$$M_i = t_i p_i' \tag{1}$$

With $t_i$ as the score vector and $p_i$ as the loading vector ($p_i$ are orthogonal and can hence be seen as $n$-dimensional coordinate system). The score vector $t_i$ represents the information content of data matrix $X$ in the coordinate system $p_i$. The PCA in this work was carried out with the NIPALS-algorithm.
A classification can be done by building the scalar product of the data matrix columns and the first two principle components and plot it in the coordinate system of the first two principle components. Data sets with similar information content are hence clustered in similar regions of the coordinate system. The classification has been done using the correlation matrix $C_{ij}$ of the Fourier components.

$$C_{ij} = \frac{\sum_{k=1}^{m} (x_{ik} - \bar{x}_i)(x_{jk} - \bar{x}_j)}{\sqrt{\sum_{k=1}^{m} (x_{ik} - \bar{x}_i)^2 \sum_{k=1}^{m} (x_{jk} - \bar{x}_j)^2}} \tag{2}$$

with $i$=1 … $n$ and $j$=1 … $n$, $x_i$ as the $i$-th column and $\bar{x}_i$ the mean of $i$-th column in the data matrix.

Fig. 6 shows the PCA results for a ceramic-on-ceramic hip prosthesis under a load of 30 kg for experiments carried out at the laboratory setup. Ceramic and metal powdery particles are used to simulate wear. It can be seen that the features can be distinguished since a clustering of experimental data can be done in the PCA results.

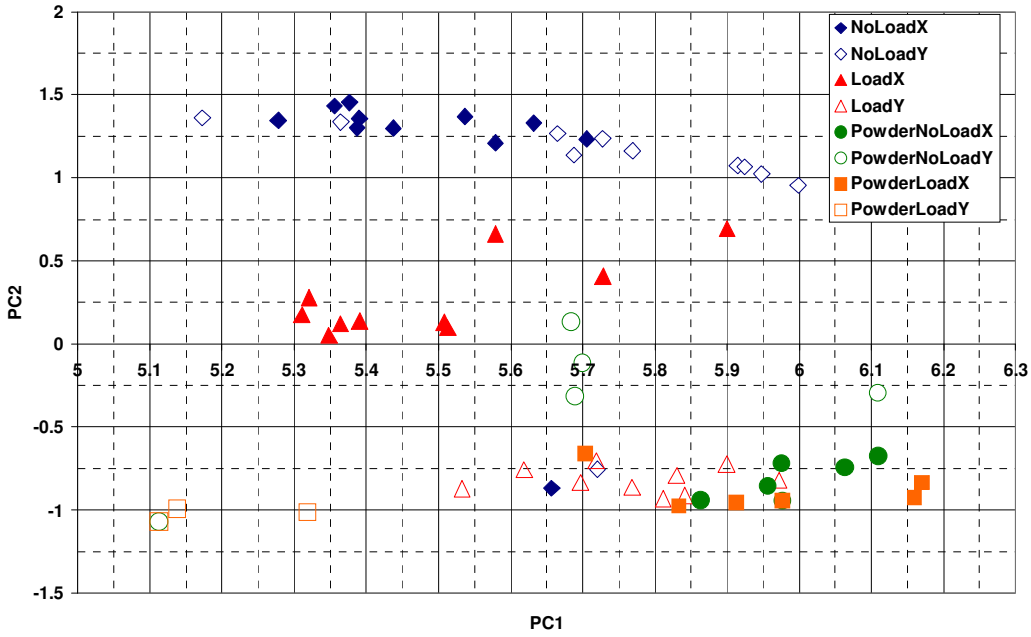
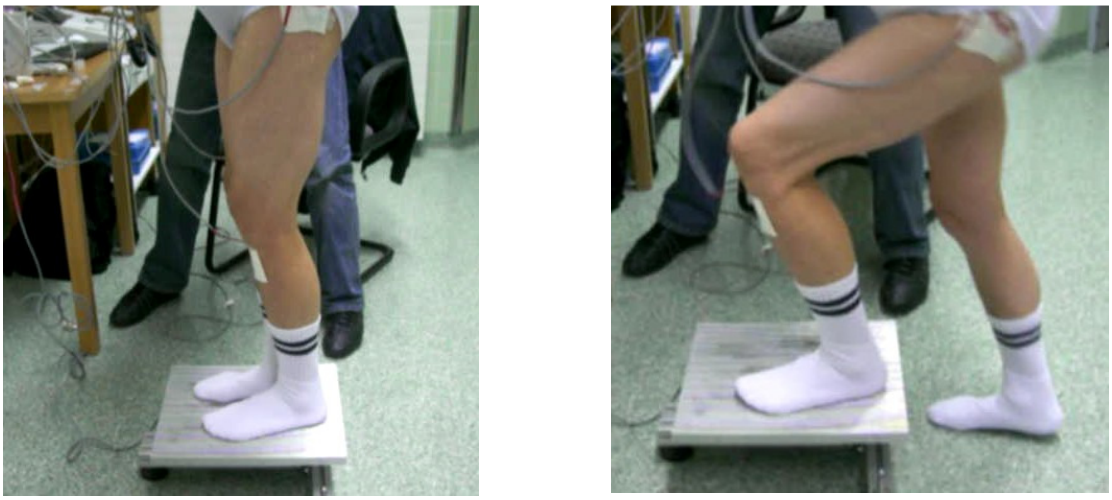



Fig. 6: PCA of measurement results from laboratory test setup for features load / no load, wear simulation (powder) / no wear simulation (no powder) for a ceramic-on-ceramic endoprosthesis

b) Measurement Results – Medical Study with Patients

For the medical study, the sensor system shown in Fig. 2 has been used to be tested with a total amount of 17 patients. For each patient, the three acceleration sensors have been mounted according to the positions in Fig. 1 (tibia, left hip, right hip) and a sensor calibration is performed using the vibration motor. The patient then carries out a predefined motion sequence by standing still before the podium, stepping onto the podium with the right and then left leg, standing still on the podium, and stepping down onto the ground with the left and then right leg.
The patient's positions during this motion sequence are shown in Fig. 7.



(a) (b)

Fig. 7: Position during the motion sequence (a): Standing still on the podium and (b): Stepping down onto the ground from the podium.

Fig. 8 to 10 show measurement results during the motion sequence of a patient with a hip endoprosthesis. The load characteristic of the load cell over time is plotted in the diagrams as well as the acceleration signal recorded with the sensor system.

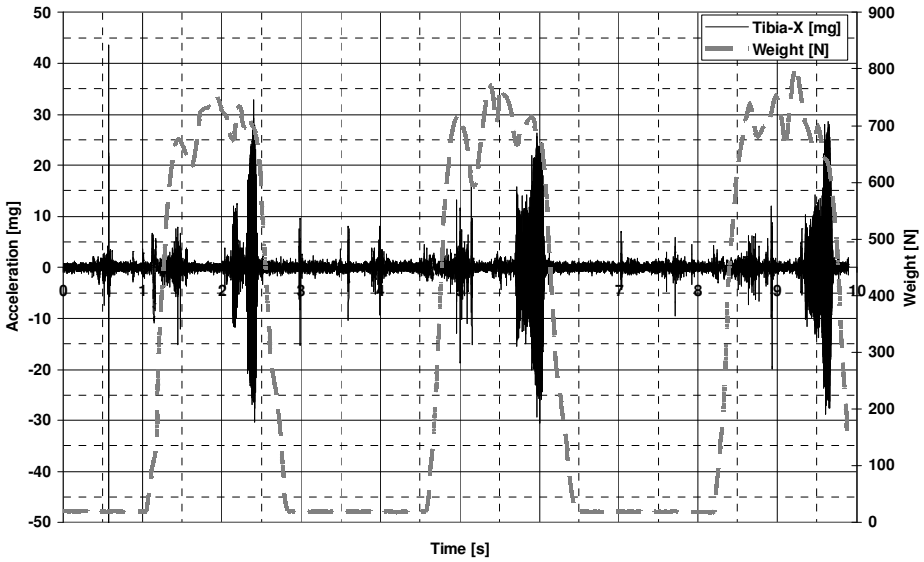



Fig. 8: Acceleration measurement results during motion sequence for the sensor placed at the patient's tibia.

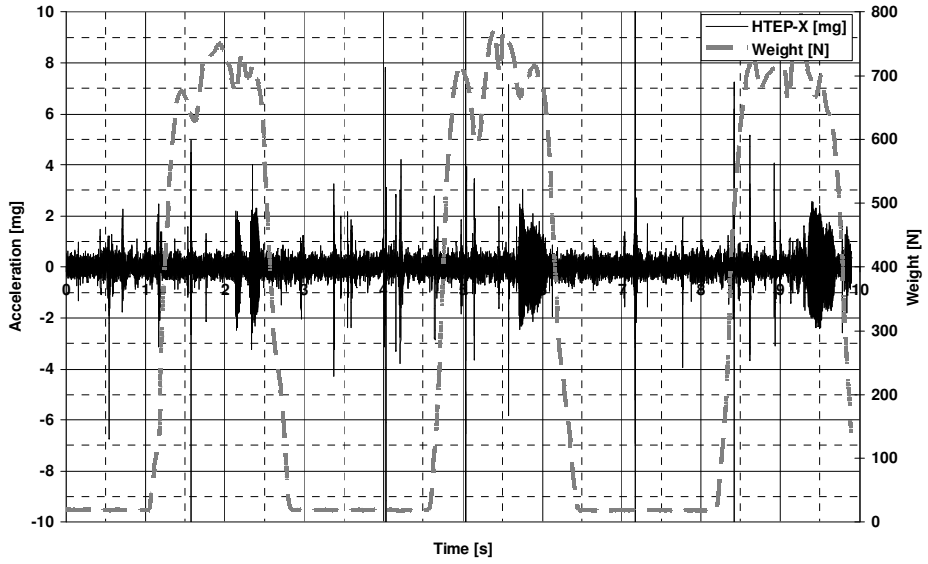



Fig. 9: Acceleration measurement results during motion sequence for the sensor placed at the patient's hip (endoprosthesis side). The weak amplitude is mainly due to scar tissue.

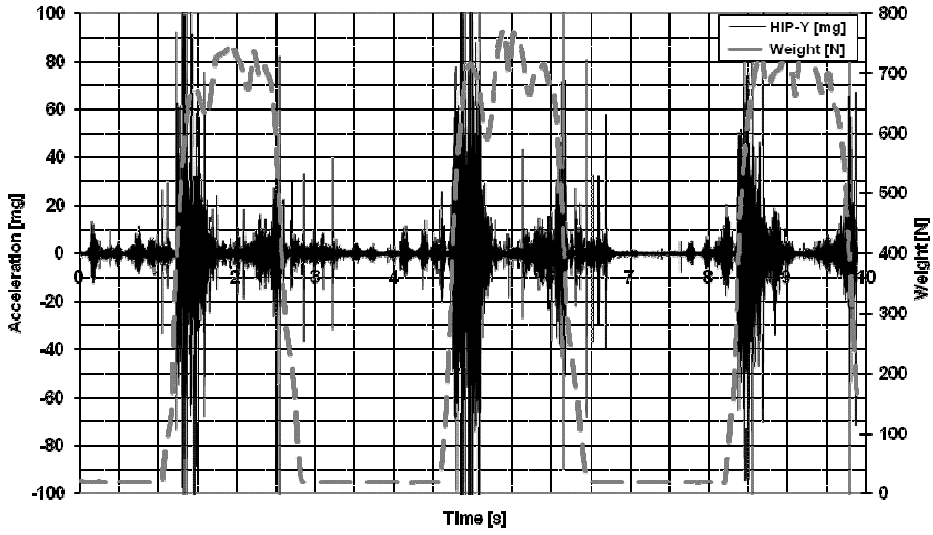



Fig. 10: Acceleration measurement results during motion sequence for the sensor placed at the patient's hip (side without endoprosthesis).

Comparing Fig. 9 and Fig. 10, both sensors are placed on soft and dampening tissue. Surprisingly, the signal amplitudes at the patient's hip without endoprosthesis exceeds the signal

amplitudes at the patient's other hip by an order of magnitude during the upward movement. We assume that this is mainly due to scar tissue.

Fig. 11 shows the power spectral density [8] plot over time. The brighter regions in the diagram indicate higher power spectral density, it can be seen that according to the motion sequence (about 2.5 s step onto the podium with the right leg, 6 s step onto the podium with the left leg, 10 s step down from the podium with the left leg) a significant frequency contribution of about 1.500 Hz is dominant in the spectral plot. These vibrations are clearly audible as a whistling noise. Evaluating the angle information of the thigh during the time steps when significant frequency contributions are dominant, spatial information about the imperfection of the endoprosthesis can be derived, allowing a non-invasive characterization of the prosthesis.

A vibration in the range of 500 Hz to 1.000 Hz precedes the whistling noise at 1.500 Hz. Both vibrations occur at the same angle – the first one during the upward and the latter one during the downward movement.

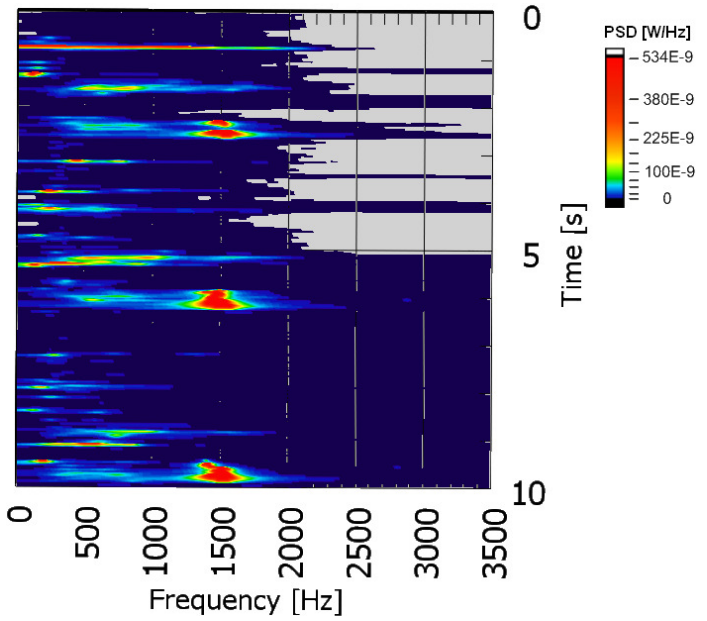



Fig. 11: Power spectral density plot over time acquired during the motion sequence.

## VI. CONCLUSIONS

This paper presents a non-invasive, acceleration based method to characterize failures in an endoprosthesis. The design and development of a suitable sensor system are described in the

paper. Measurement results for experiments carried out with a laboratory test setup and during a medical study with patients are presented. Both, method and sensor system are the basis for a reliable characterization of failure types for endoprostheses.

## ACKNOWLEDGEMENT

The authors wish to thank the "COMET K2 - Competence Centres for Excellent Technologies Programme" of the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT), the Austrian Federal Ministry of Economy, Family and Youth (BMWFJ), the Austrian Research Promotion Agency (FFG), the Country Styria and Styrian Business Promotion Agency (SFG) for their financial support.

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