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Research article

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Calculation of the elastic properties of prosthetic knee components with an iterative finite element-based modal analysis: quantitative comparison of different measuring techniques

Abstract: With the aging but still active population, research on total joint replacements relies increasingly on numerical methods, such as finite element analysis, to improve wear resistance of components. However, the validity of finite element models largely depends on the accuracy of their material behavior and geometrical representation. In particular, material properties are often based on manufacturer data or literature reports, but can alternatively be estimated by matching experimental measurements and structural predictions through modal analyses and identification of eigenfrequencies. The aim of the present study was to compare the accuracy of common setups used for estimating the eigenfrequencies of typical components often used in prosthetized joints. Eigenfrequencies of cobalt-chrome and ultra-high-molecular weight polyethylene components were therefore measured with four different setups, and used in modal analyses of corresponding finite element models for an iterative adjustment of their material properties. Results show that for the low-damped cobalt chromium endoprosthesis components, all common measuring setups provided accurate measurements. In the case of high-damped structures, measurements were only possible with setups including a continuously excitation system such as electrodynamic shakers. This study demonstrates that the iterative back-calculation of eigenfrequencies can be a reliable method to estimate the elastic properties for finite element models.

Keywords: eigenfrequency; finite element analysis; validation; Young's modulus.

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Introduction

In Germany, in 2011 the number of primary total hip replacements was 213,935 and for primary total knee replacements it was 158,207. Between 2007 and 2011, the number of primary total hip replacements and primary total knee replacements increased by 5% and approximately 8%, respectively [22]. Although being successful procedures, clinical evidence of loosening and component wear still occurs [3]. Computer simulations such as finite element (FE) analysis have occasionally been used to predict changes in stress and strain patterns in periprosthetic bone structures and contact mechanics after total joint replacements (TJRs) [1, 2, 11, 16, 21, 23, 26], resulting in bone remodeling [17], and their relationship to component loosening [1, 16, 27]. Although some studies are in good accordance with clinical observations, most rely on material properties of prosthetic components, which are adapted from the literature or provided by the manufacturer. However, the solution of biomechanical FE analyses can only be used with confidence after careful validation of the model's behavior, in particular related to the assignment of its material properties [7, 24]. Owing to their wide range, values of the material properties from the literature may not always provide a reliable basis for FE analyses [8, 15, 20, 25], especially when new materials are involved. One procedure to assign material properties for FE models is to iteratively adjust them through back-calculation until the model's predictions match an experimentally measured quantity. This was done, for example, for micro-FE

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studies of cancellous bone biopsies, where the compressive apparent modulus of the whole structure was used to identify bone tissue modulus at the tissue level. Bayraktar et al. [4] used an iterative matching procedure with the experimental compression modulus of the bone biopsies as the match criterion. A similar iterative back-calculation

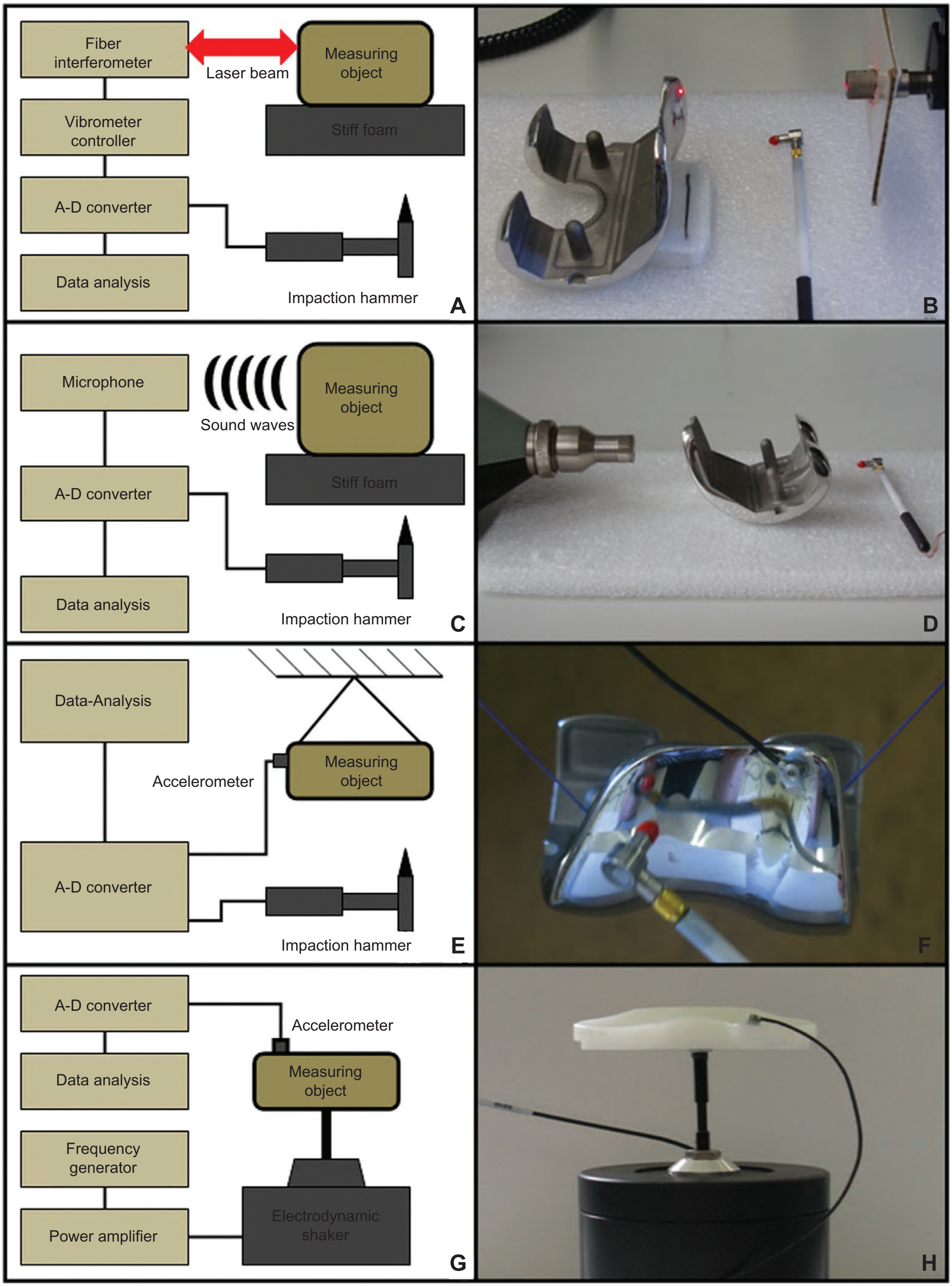

Figure 1 Schemes of the tested measuring setups: (A, B) setup A, (C, D) setup B, (E, F) setup C, (G, H) setup D.

approach was used to identify the elastic modulus of long bone structures with modal analysis and predicted eigenfrequencies [12, 23]. Commonly used as a non-invasive technique to measure the elastic properties of materials, modal analysis was already applied to identify Young's modulus in biological materials, by making a comparison between the experimentally determined and the numerically calculated eigenfrequencies of the structure [23].

Several setups have been developed for the identification of eigenfrequencies with modal analysis. Neugebauer et al. [19] have used an electrodynamic shaker for the excitation of the structure and a three-dimensional (3D) laser vibrometer for frequency measurement. An accelerometer and microphone pair is also commonly used to determine eigenfrequencies [12, 13]. Other measuring variants also include impaction hammers for the purpose of excitation [5, 23].

Because there is a variety of setup possibilities, the aim of the present study was to conduct an initial validation by comparing the common hardware pairings used for eigenfrequency identification and quantification of the elastic properties of total joint replacement components and to identify a setup which can measure high-damped structures as ultra-high-molecular weight polyethylene (UHMWPE), which is necessary to validate the whole material properties of a total joint replacement. Moreover, the aim of this study was to give an overview of which setup is accurate enough to be used in future studies especially for eigenfrequency identification in worn and degraded components or biological tissues.

Materials and methods

Test preliminaries

Four common testing setups were compared in this study (Figure 1): (setup A) impaction hammer-laser vibrometer, (setup B) impaction hammer-microphone, (setup C) impaction hammer-accelerometer, and (setup D) electrodynamic shaker-accelerometer. The measurements were performed with a cobalt chromium (CoCr) femoral component and a tibial insert (UHMWPE, GUR 1020) of the total knee replacement system Columbus© (Aesculap Orthopaedics, Tuttlingen, Germany). Each structure was measured and analyzed five times at one point of the structure and these data were used to determine the average of the first eigenfrequency. An overview of each testing setup is briefly described below and shown in Table 1. To ensure highest accuracy, the sensor position and the measuring point for the laser vibrometer were placed at the position of the highest deformation on the first eigenfrequency, which was verified in the FE model (Figure 2). For the femoral component there were two possible positions: the dorsal condyles and the highest point of the ventral edge of the component. For all systems tested, the measuring point for the femoral component was the highest point of the ventral edge. The tibial insert showed the largest deformation at the dorsal side and therefore this position for the sensor and the measuring point was chosen.

Measuring setup: impaction hammer-laser vibrometer (setup A, Figure 1A, B)

This measuring setup consisted of an impaction hammer (086E80, PCB Piezotronics, Inc., Depew, NY, USA), a single point fiber interferometer and its associated vibrometer controller (OFV-512 and OFV-5000, Polytec GmbH, Waldbronn, Germany). The endoprosthetic components were positioned on stiff foam to approximate free-boundary conditions. The excitation of the measuring object was performed by impacting the hammer vertically.

Table 1 Overview of the four measuring setups.

	Setup A	Setup B	Setup C	Setup D
Measuring system	Laser vibrometer	Microphone	Piezoelectric accelerometer	Piezoelectric accelerometer
Excitation system	Impaction hammer	Impaction hammer	Impaction hammer	Electrodynamic shaker
Simulation of free-boundary condition of the structure	Positioning on stiff foam	Positioning on stiff foam	Hanging at tenuous synthetic strings	Directly fixed at a low oscillating point to the shaker
Number of measurements	n=5	n=5	n=5	n=5
Software	LabVIEW 2010 (data acquisition and data analysis)	LabVIEW 2010 (data acquisition and data analysis)	DeweFRF6.6 (data acquisition and data analysis)	Dewesoft 6.6.7 (data acquisition) OriginPro7G (data analysis)

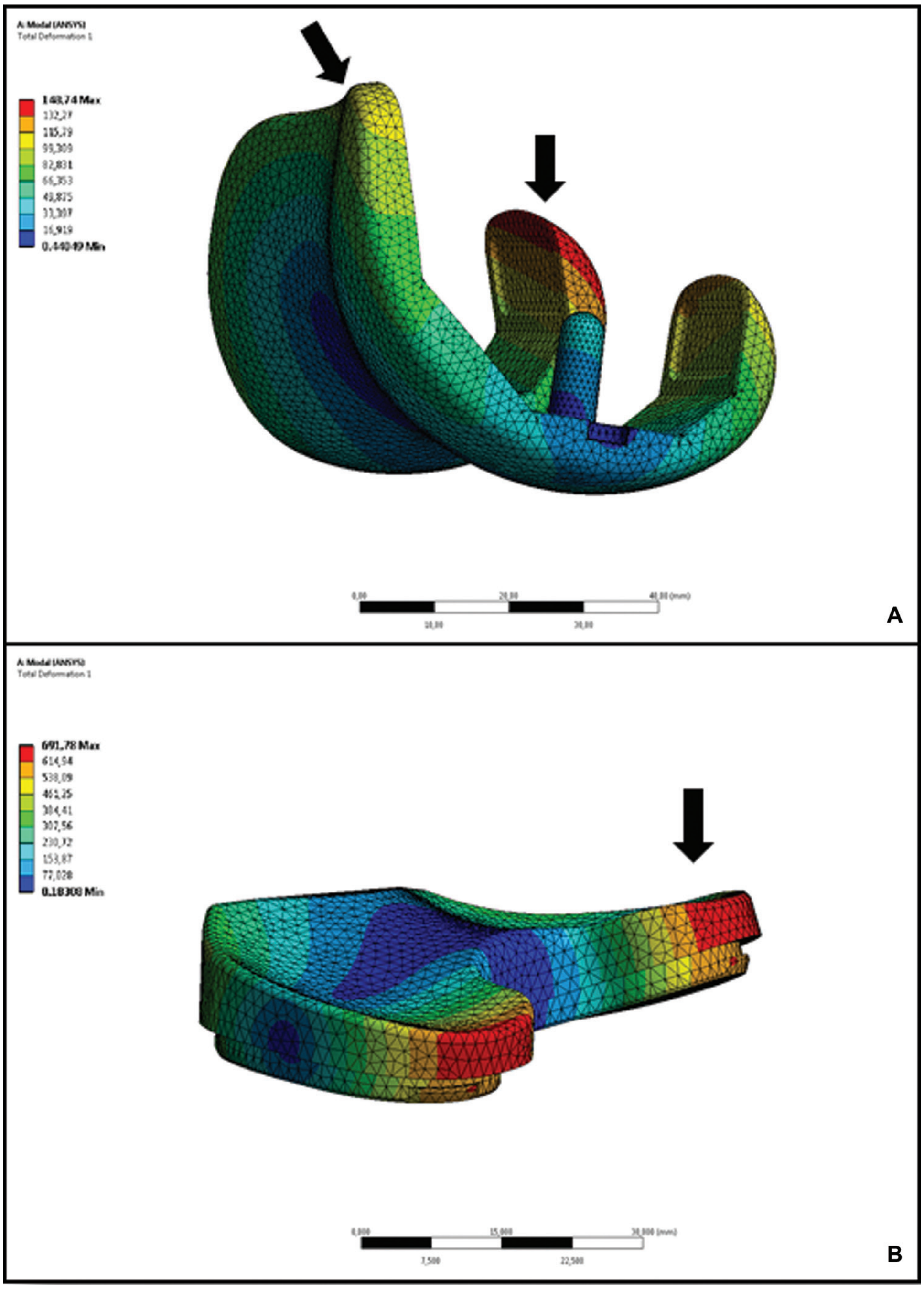

Figure 2 Finite element model showing total deformation on the first eigenfrequency
(A) Femoral component showing two points of the largest deformation: the dorsal condyles and the highest point of the ventral edge.
(B) Tibial component showing the largest deformation on the dorsal side.

Measuring setup: impaction hammer-microphone (setup B, Figure 1C, D)

The impaction hammer used for excitation in setup A was paired with a microphone impulse precision level meter (type 2209, Brüel and Kjær, Naerum, Denmark) for measuring of eigenfrequencies. The positioning of the endoprosthesis components to approximate free-boundary conditions as well as their excitation follow the same approach as implemented in setup A.

Measuring setup: impaction hammer-accelerometer (setup C, Figure 1E, F)

As a variant of setup A and setup B, the impaction hammer was paired with a piezoelectric accelerometer (AP2019, AP Tech, Napa, CA, USA). To simulate an unconstrained free-running structure, the endoprosthetic components were suspended with synthetic strings to a test rig. After adhesive fixing of the accelerometer using wax, the measuring object was excited by the impaction hammer.

Measuring setup: electrodynamic shaker-accelerometer (setup D, Figure 1G, H)

Vibrational excitation was performed using an electrodynamic mini-shaker type 4810 and an associated power amplifier type 2719 (Brüel and Kjær), and measurement of eigenfrequencies was carried out using the same accelerometer as in setup C. The endoprosthetic CoCr femoral component and UHMWPE tibial insert were directly fixed on the shaker through a short push rod. To ensure approximately free-boundary conditions, care was taken to choose a low oscillating fixing point. The structure as well as the accelerometer was adhesive-attached by wax. A single-point excitation was adopted for excitation of the structure with the shaker.

Iterative FE-based procedure to compute Young's modulus

The values of the averaged first eigenfrequencies, measured by several test setups, were used in an iterative FE-based procedure for the identification of the elastic modulus [23]. Based on computer-aided design (CAD) files of the manufacturer, FE models of both components (femoral CoCr component and UHMWPE tibial insert) were constructed in FE software Ansys 13.0 (Ansys, Inc., Canonsburg, PA, USA), and meshed with quadratic tetrahedral elements (Figure 3). A sufficient high mesh accuracy of the FE models was ensured by convergence studies of meshes. The final mesh for the femur component had

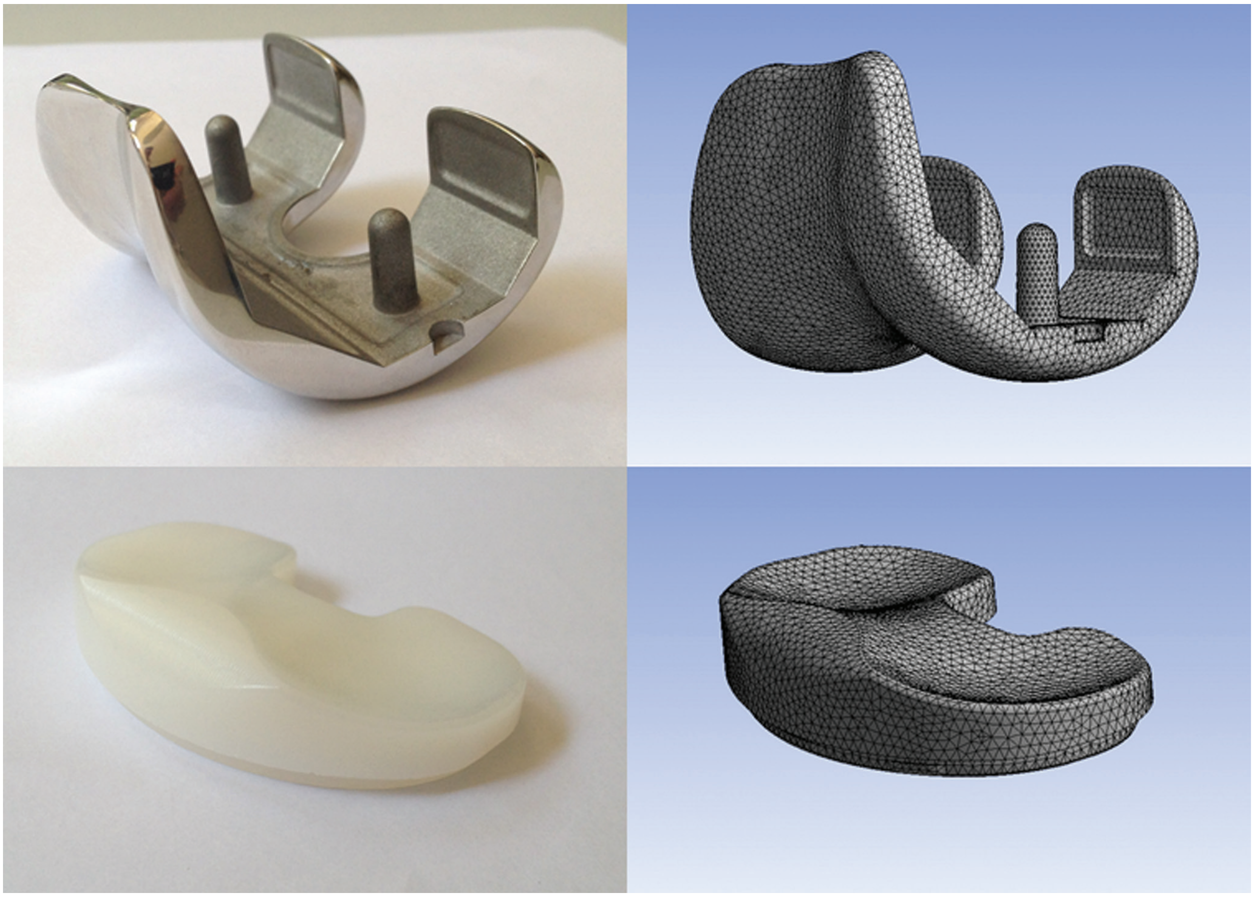

Figure 3 Endoprosthesis components: (left) real components, (right) numerical models.

a maximum element size of 0.5 mm and 83,855 elements and for the UHMWPE Inlay an element size of 0.5 mm and 62,565 elements. To simulate free-boundary conditions in the FE model, no supports or loads were applied to the structural model.

In addition to Young's modulus, material density and Poisson's ratio are also important factors for a valid numerical model. Therefore, the densities of the components were determined by measuring the mass of the components and the given volume of the components from the CAD data [13]. These FE models provided the basis for the adjustment of Young's modulus by their specific eigenfrequencies. Using these FE models, a modal analysis (Modal module, Ansys 13.0) was performed, which allowed the prediction of the first eigenfrequency of modeled structures, using linear isotropic elastic material behavior with initial values for the elastic modulus, Poisson's ratio and density based on the literature, measurement and manufacturer's data (CoCr: E_0=220,000 MPa, v=0.3, ρ=8.0 g/cm^3; UHMWPE: E_0=300 MPa, v=0.46, ρ=0.93 g/cm^3) [8, 13, 15, 20, 25]. The elastic modulus of the femoral component and tibial insert FE models were then iteratively adjusted and modal analysis was performed again until the predicted first eigenfrequency matched the one measured from each test setup, with a matching criterion of ≤1 Hz. For each measured component, the calculated elastic moduli of the matching eigenfrequencies could then be compared to those of the manufacturer, to assess the accuracy of the four testing setups.

Results

The first eigenfrequencies of both components measured by the four setups were in the range of 1731 Hz–1738 Hz for the femoral component, and 1349 Hz for the tibial insert (Figure 4). For the tibial insert, it was only possible to measure the eigenfrequencies with the electrodynamic shaker-accelerometer setup.

Using the iterative FE-based procedure, these resulted in predictions for the elastic modulus between 215,625 MPa and 217,000 MPa for the CoCr femoral component and 312.5 MPa for the UHMWPE tibial insert (Figure 5). The mean Young's modulus of all four measurements for the CoCr femoral component was 216,625 MPa with a standard deviation of 669 MPa.

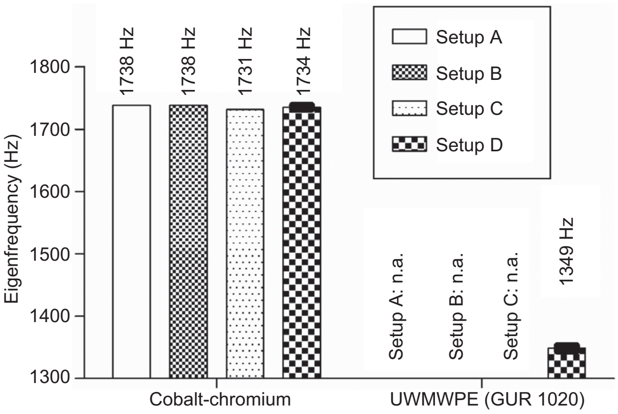

Figure 4 Mean first eigenfrequencies of the knee endoprosthesis components, measured with the four tested setups.

Discussion

The aim of this study was to evaluate the accuracy of different measuring setups to provide a quantification of the elastic properties of total joint replacement materials through experimental eigenfrequency identification coupled with an iterative FE-based modal analysis. Based on results for the CoCr component (CoCr29Mo6), the minimal differences in Young's modulus between the manufacturer's supplied, common values used in the literature [6, 13, 16] and the predicted values resulting from the eigenfrequencies measured with each setup suggest that all four measuring setups are qualified for eigenfrequency determination of such low-damped structures. No differences shown between setups C and D in Young's modulus for the CoCr component suggest that the method of excitation does not play a crucial role in quantification of eigenfrequencies for this material. This suggestion is consistent with Taylor et al. [23] and Neugebauer et al. [19], who used

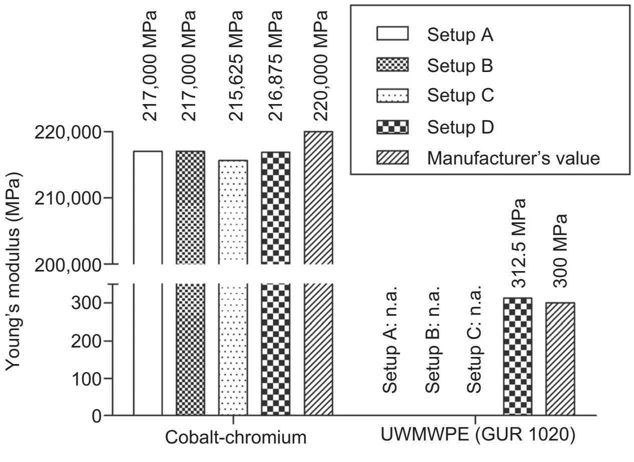

Figure 5 Young's moduli of the knee endoprosthesis components arise from the first eigenfrequencies, measured with the four tested setups.

different excitation methods to measure eigenfrequencies in bone and both showed sufficient quality.

Furthermore, for such low-damped structures, contact measuring systems such as accelerometers have minimal influence on measuring results and could be reliable alternatives to expensive contactless systems such as laser vibrometers. The small difference in eigenfrequencies between contact measuring and non-contact measuring systems may result from adhesive fixing of the accelerometer by mechanical impedance of the wax. The small weight of the accelerometer (0.13 g) and the slight difference in the boundary conditions of the measuring setups may also influence measuring of eigenfrequencies. A 7-Hz difference in the first eigenfrequency and therefore 1.375 MPa difference in the calculated Young's modulus may suggest that these influences between the different setups and the FE model are not significant.

However, regarding the UHMWPE tibial insert, measurements could only be performed using the electrodynamic shaker and the accelerometer (setup D), due to the highly damped nature of the material. Therefore, the period of oscillation is approximately 20 ms and is too small to obtain enough relevant measuring points for identification of eigenfrequencies, in the case of carrying out excitation with an impact hammer. This suggests that eigenfrequencies of high-damped TJR components may only be accurately measured when the structure is continuously excited with an electrodynamic shaker. Young's modulus for UHMWPE has a wide range in the literature due to different manufacturing procedures and chemical characteristics [14]. The resulting Young's modulus of the UHMWPE inlay used in this study is in good agreement with the material data that was provided by the manufacturer and is also used in other studies that researched similar material [9, 10, 18].

Overall, the selection of the measuring setup for eigenfrequency identification in a complex system with many components should be carefully carried out to ensure that all components are measurable.

Unquestionably, an important limitation of this study is that predictions of eigenfrequencies largely depend on the geometrical accuracy of the FE model and the material model used. In our study, components were assumed linear elastic and isotropic. Component geometrical defects and heterogeneous material properties may require more complex setups and numerical analyses. Despite this limitation, we believe that the presented approach and guidelines will be useful in providing refined material properties for typical prosthetized components, which cannot be achieved by direct means or rely on data provided by manufacturers. Future studies will aim at understanding how geometrical imperfections, such as those occurring for worn out UHMWPE inlays, can affect the accuracy of eigenfrequency measurements, and how these could be included in more reliable predictions of material behavior.

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