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Influence of cementless hip stems on femoral cortical strain pattern depending on their extent of porous coating

Einfluss zementfreier Hüftstiele auf das Spannungsmuster der Femurkortikalis in Abhängigkeit von der Ausdehnung ihrer Oberflächenstrukturierung

Martin Ellenrieder[1,*], Erwin Steinhauser[2], Rainer Bader[1] and Wolfram Mittelmeier[1]

[1] Department of Orthopaedics, University of Rostock, D-18057 Rostock, Germany

[2] Munich University of Applied Sciences, D-80335 Munich, Germany

Abstract

The extent of porous coating of cementless total hip stems is held responsible for radiological periprosthetic changes, the rate of thigh pain, and even its long-term success. However, there is only sparse knowledge on how the biomechanical loading conditions of the femur are influenced by the extent of porous coating in the early phase after implantation of a cementless hip stem. Aiming to evaluate the effect of surface structuring on the strain pattern of the femur, we implanted three anatomic hip stems with different extents of porous coating (full, two-thirds proximal, and penguin type) in second-generation composite femora coated with a photoelastic layer. A cortical strain mapping was conducted before and after insertion of the implants under standardized loading conditions considering relevant muscle forces. The results of the statistical analysis of three different implantation sequences proved that composite femora are suitable for repeated measurements within the applied experimental setup. Cortical strain changes including stress-shielding effects medially (-60%) and laterally (-50%) were validated with a cadaver femur. The extent of porous coating had no significant influence on the surface strain pattern for an immediate postoperative situation.

Keywords: cadaver femur; cementless hip endoprostheses; composite femora; experimental study; photoelastic coating.

*Corresponding author: Dr. Martin Ellenrieder, Department of Orthopaedics, University of Rostock, Doberaner Str. 142, D-18057 Rostock, Germany
Phone: +49-381-494 9326
Fax: +49-381-494 9397
E-mail: martin.ellenrieder@uni-rostock.de

Zusammenfassung

Die Ausdehnung des porös beschichteten Oberflächenanteils wird beim zementfreien Hüftstiel für die radiologisch sichtbaren periprothetischen Veränderungen, die Inzidenz von Oberschenkelschmerzen und sogar dessen Standzeit verantwortlich gemacht. Dennoch ist bisher nur wenig darüber bekannt, ob bereits in der frühen postoperativen Phase die biomechanische Lastsituation am Femur durch die Ausdehnung der Oberflächenstrukturierung beeinflusst wird. Mit dem Ziel, den Effekt der porösen Strukturierung auf das corticale Dehnungsmuster des Femur zu evaluieren, implantierten wir drei anatomische Hüftstiele mit unterschiedlichem Ausmaß der porösen Strukturierung (voll, zwei Drittel proximal und „pinguinförmig“) in photoelastisch beschichtete Composite Femora der II. Generation. Vor und nach Einbringen der Implantate wurde eine corticale Dehnungsvermessung unter standardisierten Lastbedingungen und Berücksichtigung wichtiger Muskelkräfte durchgeführt. Die Ergebnisse der statistischen Auswertung dreier verschiedener Implantationsreihenfolgen bestätigten zunächst die grundsätzliche Eignung der Composite Femora für wiederholte Messungen mit dem vorliegenden Prüfaufbau. Stress-shielding Effekte einschließlich einer Reduktion der corticalen Dehnungen medial (-60%) und lateral (-50%) wurden anhand eines Humanfemur validiert. Die Ausdehnung der porösen Strukturierung der Implantatoberfläche hatte keinen signifikanten Einfluss auf das Oberflächendehnungsmuster unter Annahme einer unmittelbar postoperativen Lastsituation.

Schlüsselwörter: Composite Femora; experimentelle Studie; Humanfemur; Photoelastik; Zementfreie Hüftendoprothesen.

Introduction

The rising number of failure cases of cemented hip endoprostheses in young patients in the 1980s stirred up the interest for cementless hip stems [47, 56]. The first generation of anatomically shaped cementless stems had a complete or extended porous coating of their surface [16]. However, the clinical impact of periprosthetic bone resorption particularly seen with fully coated stems has not been definitely clarified

[40]. Aiming to reduce stress-shielding effects and resorptive bone remodeling, the second generation with only proximal coating was introduced [14, 39, 41] and was followed by a third generation with an additional hydroxyapatite layer [38]. Furthermore, a more proximal load transfer should prevent persistent thigh pain for which a prevalence of up to 39% is reported after cementless total hip replacement [1, 4, 11, 23, 42, 47]. However, it is controversially discussed whether that discomfort is actually associated with the extent of porous coating [17, 23, 39, 40]. Well-fixed fully coated stems lead to a more distal load transfer and cortical hypertrophy [14, 16, 22, 40, 63], whereas proximally coated stems show greater interface micromotion of the distal tip of the endoprosthesis [1, 15, 33, 56]. The importance of these observations must be evaluated in view of many other influences on the prevalence of thigh pain after total hip arthroplasty (THA). Several authors emphasize the contribution of factors related to patients (e.g., obesity, depression), implants (e.g., material, design), or operative techniques (e.g., overreaming) [4, 18, 35, 37, 39, 40, 55].

Moreover, the surgical revision in the case of aseptic loosening should be easier with a smoother surface at the diaphyseal part of the implant, causing less damage to the periprosthetic bone stock and reducing complications such as trochanteric avulsion fractures [52]. Nevertheless, a circular proximal porous coating should reduce the effective joint space and migration of wear particles [12, 29, 53]. The controversial results of clinical and radiological follow-up studies have still left over the question which concept is superior from the biomechanical and clinical view [40]. Experimental studies with autopsy retrievals demonstrated the influence of the extent of porous coating on periprosthetic bone density and structure as well as interface micromotion [15, 16]. However, the effects of the extension of surface structuring regarding the early postoperative period, which prepares the ground for bone remodeling, still remain unclear.

Aiming to evaluate the impact of hip endoprostheses on the biomechanics of the femur, several studies basically confirm composite femora to be suitable for such investigations [9, 27, 43, 59, 60]. Extensive testing revealed no significant difference between second-generation composite femora and fresh-frozen or dried-rehydrated cadaver femora [9]. Though overall interfemoral variability of composite femora is reported to be up to 200 times lower compared with human femora, some variations are reported for the medial-proximal region and their deformation response under certain conditions [9, 59, 60]. Hence, an experimental study using composite femora should comprise the data of the intact femora as a baseline [60]. An additional testing of at least one cadaver femur seems reasonable when using a new test setup. No literature data are available concerning the influence of repeated use of composite femora after removal and reinsertion of hip stems. However, with both composite and human femora, the photoelastic coating technique is well established for cortical strain measurement since double refraction properties of certain plastics have been discovered in the 1930s [21, 28, 30, 32, 44, 46, 57, 58, 64].

The anatomic cementless GHE hip stem (ESKA Implants AG, Lübeck, Germany) used in the present study provides three different alternatives in surface structuring. The coverage with a three-dimensional (3D) interconnecting trabecular mesh can comprise either the whole stem or only the proximal two-thirds with or without an open area on the medial side. This investigation was aimed at comparing the influence of the extent of surface structuring on femoral cortical strain pattern. This is important as periprosthetic biomechanical conditions influence bone remodeling and implant survival.

Our experimental study had three main purposes. First, the suitability of the second-generation composite femora for tests with sequential implantations of hip stems was evaluated. Second, the femoral cortical strains after insertion of the GHE hip stem were compared to the intact bones in terms of the extent of porous coating; an immediate postoperative situation was assumed. Finally, the femoral cortical strain changes and stress-shielding effects after implantation of the GHE hip stem in a cadaver femur were analyzed. Hence, cortical strain measurement of the photoelastically coated femora was conducted under reproducible statistical loading conditions simulating relevant forces.

Materials and methods

Implants and insertion sequence

The cementless anatomic GHE hip stem (size 4, length 120 mm) is made of a cobalt-chromium alloy and has an anatomically shaped design. The implant body is porous coated with a 3D interconnecting trabecular mesh (Spongiosa Metal® II; ESKA Implants AG, Lübeck, Germany). The trabecular mesh covers the hip stem completely (“full”), two-thirds proximally (“proximal”), or proximal with an open area medially (“penguin type”) as shown in Figure 1. Due to its anatomic design, the stem is lateralized and available as a left and right version. For the present study, only left lateralized hip stems and left femora were used. All endoprostheses were inserted by the senior author using the original instruments. The schedule for the implantation sequence was arranged to represent three out of six possible triplet combinations with n=3 femora for each group (Table 1). X-rays from anteroposterior and lateral views were conducted after insertion of every hip stem to verify a correct implant position. With an “XL” head, the femoral offset (48 mm) and the vertical position of the hip center in relation to the tip of the greater trochanter was reproducibly reconstructed and compared to the intact femora. The position of the hip stems in relation to the femora and the measuring points is illustrated within Figure 3A and B.

Femora and photoelastic coating

As specimens, nine adult model composite femora (Pacific Research Laboratories Inc., Sawbones Europe AB, Malmö, Sweden) (second generation, length 485 mm, left side, type 3106) were photoelastically coated. The coating consisted of a two-component material (PL-1 and PLH-1; Photoelastic

Figure 1 Anatomic GHE hip stem.
(A) Medial aspect: full (left), proximal (middle), and penguin type (right). The stems are covered with a trabecular mesh (Spongiosa Metal II) to different extents. The geometry of the implant body is identical for all three stems (anatomical shape, left lateralized, size 4, length 120 mm). (B) Anterior aspect: proximal.

Division, Measurements Group Inc., Raleigh, NC, USA) with a k-factor of 0.08 and a Young's modulus of 288 kN/cm^2. Four 1.8 mm thick sheets were cut using a template and attached to the femora with a colloid-containing adhesive (PC-10, PCH-10; Photoelastic Division, Measurements Group Inc., Raleigh, NC, USA).

On each side of the femur (anterior, posterior, medial, and lateral), 25–27 measuring points were marked circularly using a marking gauge in a parallel direction to the femoral axis. The vertical height between the measuring points was 1 cm at the proximal femur down to the mid-diaphysis and 2 cm at the distal half of the femur. Measuring point "MP 1" was adjusted to the height of the lesser trochanter; "MP 0" corresponded to the basis of the neck resection line (Figure 2).

Table 1 Implantation sequence for the nine composite femora representing the three out of six possible triplet constellations, which allow each of the implants to stand exactly once at the first, second, and third position of the ranking order.

	1. Implant	2. Implant	3. Implant	Triplet
Femur 1	Full	Penguin	Proximal	Triplet 1
Femur 2	Full	Penguin	Proximal	
Femur 3	Full	Penguin	Proximal	
Femur 4	Proximal	Full	Penguin	Triplet 2
Femur 5	Proximal	Full	Penguin	
Femur 6	Proximal	Full	Penguin	
Femur 7	Penguin	Proximal	Full	Triplet 3
Femur 8	Penguin	Proximal	Full	
Femur 9	Penguin	Proximal	Full	

The hip stems are either fully (full), proximally (proximal), or penguin-type (penguin) coated as shown in Figure 1.

Photoelastic strain mapping was conducted with a reflection polariscope (model 031; Photoelastic Division, Measurements Group Inc., Raleigh, NC, USA) and a Babinet-Soleil null-balance compensator (model 232) [50]. The waveform phase of polarized light is modified when passing through the photoelastic coating under loaded conditions. Absolute value and algebraic sign of the difference in transverse and longitudinal principal strains quantify the magnitude and direction of the elastic deformation of a specimen. The difference in principal strains measured in this study is referred to simply as "strains" in the following. For each intact femur, cortical strain measurement was performed for all measuring points under standardized load. After insertion of the endoprostheses, strain measurement was repeated with the unloaded femur to determine the magnitude and direction of the assembly strains [21, 32]. Finally, strain measurement was conducted with the implanted hip stem under load. Femoral assembly strains and strains under load were measured with every hip stem. Statistical comparison of the strains before and after the implantation of the hip stems was preceded by a correction for assembly strains if substantial.

In order to validate the results, a fresh-frozen human cadaver femur with almost matching size was tested (male, 63 years, 173 cm, 81 kg, length 476 mm, centrum-collum-diaphysis (CCD) angle 122°, femoral offset 45 mm). While thawing, the femur was cleaned of soft tissue and periosteum. After sealing the holes of the nutrient vessels with a thin adhesive layer (PC-10), further preparation and photoelastic coating were identical with those of the composite femora. Only one hip stem (proximal) was implanted due to a significant loss of cancellous bone after extraction of the stem. Preparation and all tests with the cadaver femur were completed within 48 h. Corresponding to the composite femora, three conditions were determined: strains with the intact femur under load and strains after insertion of the hip stem with and without loading.

Loading conditions

The experimental setup was designed to meet the *in vivo* data of Bergmann et al. [2], Brand et al. [3], and Damm et al. [10] for the heel-strike maximum during walking. A resulting hip force of 2.4 kN was applied corresponding to 270% body weight of a 90 kg male patient. The femora were mounted with 12° adduction on a platform with three degrees of rotational freedom. The setup was constructed for reproducible application of a 32 N·m moment as it occurs *in vivo*, resulting from the direction of the hip force in the sagittal plane during heel strike [2]. Moreover, according to the results of several experimental and finite element (FE) studies [8, 13, 19], the most important muscle straps are the abductors and the iliotibial band.

Statistical analysis

The strains were detected for every measuring point on the anterior, posterior, medial, and lateral sides. The statistical

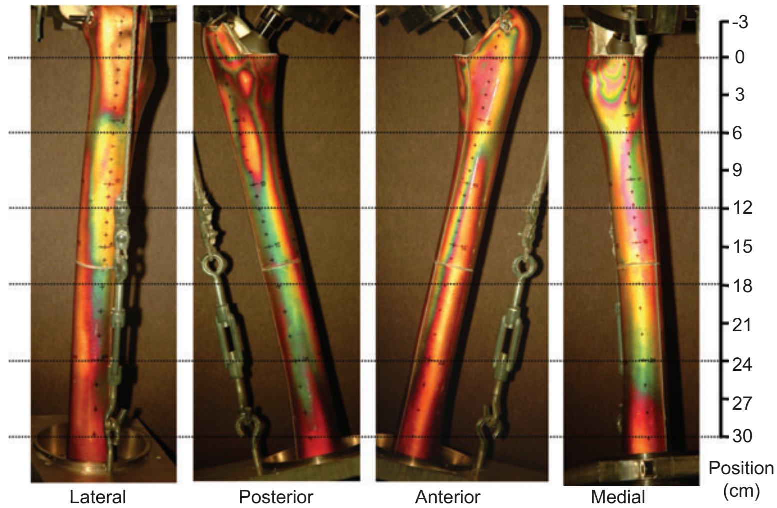

Figure 2 Composite femur with photoelastic coating and 25–27 measuring points on each side under loaded conditions – hip force (2.4 kN), resulting torque moment (32 N·m), abductors, and the iliotibial band. The measuring points "one" (MP 1) are located at the height of the lesser trochanter. The distance between the measuring points is 1 cm (proximal femur to mid-diaphysis; MP 3–MP 16) and 2 cm (mid-diaphysis to distal femur; MP 18–MP 30).

analysis comprises the comparison of the cortical strains of the intact femur and after the implantation of the hip stems under loaded conditions. The evaluation included the variance analysis for repeated measurements (measuring points of each side) for one factor (implant type or implantation sequence). Either the sphericity-assumed or the Greenhouse-Geisser test was used for variance analysis depending on the result of Mauchly's test of sphericity (two-sided, 5% level of significance). The calculation was carried out with the software package SPSS (SPSS Inc., Chicago, IL, USA).

An additional statistical comparison of the strains before and after stem insertion was based on a 95% confidence interval (CI) of the intact femora. It facilitates the illustration of the implant-correlated effects on femoral strains concerning their extent and relative value.

Results

Implantation sequence

The comparison of the influence of the three hip stem designs (full, proximal, and penguin type) was preceded by an analysis of the three triplet constellations (Table 1). No statistical difference was found between the three design groups concerning their strain pattern on the medial ($p=0.96$), lateral ($p=0.57$), anterior ($p=0.68$), and posterior ($p=0.97$) sides of the femur. Moreover, neither the inspection nor the X-ray analysis conducted with every implant-femur combination revealed a marked damage of the polyurethane foam of the femur or a change of the implant position in the course of the experiments by changing the hip stems.

Intact femora versus implanted femora, and comparison of the three stems

With all three types of hip stems (full, proximal and penguin type; n=9 for each), a significant change ($p<0.001$) in the cortical strain pattern was observed by comparing the intact femora on the medial and lateral sides proximally (Figure 3A and B). For the most proximal measuring points (MP 1 to MP 3), a compressive strain reduction of about 60% was registered medially, whereas tension strains laterally were reduced by about 50%. The exact values for particular measuring points are given in Tables 2 and 3. On the anterior side, a marked increase in tension strains was found locally between MP 3 and MP 6, corresponding to the distal portion of the proximal half of the hip stems after implantation. At the height of MP 6, the increase averaged 21% (full), 33% (proximal), and 26% (penguin type) as compared with the mean value of the unresected femora. On the posterior side, a kind of mirror image strain pattern was found with a minor decrease in tensile strains at the same height. Strain readings after stem insertion on the anterior and posterior sides stayed within the 95% CI of the intact femora; the differences were not significant (anterior: $p=0.14$; posterior: $p=0.18$).

As a result, the three groups were seen as equivalent, establishing a collective of n=9 for each type of porous coating pattern. The pairwise statistical comparison of the three groups among each other (full, proximal, and penguin type; n=9 for each stem) revealed no difference in the strain pattern on the medial ($p>0.05$), lateral ($p>0.05$), posterior ($p>0.05$), and anterior sides ($p>0.05$) for each test.

Cadaver femur

First, after photoelastic coating, the unresected fresh-frozen cadaver femur was measured under standardized loading

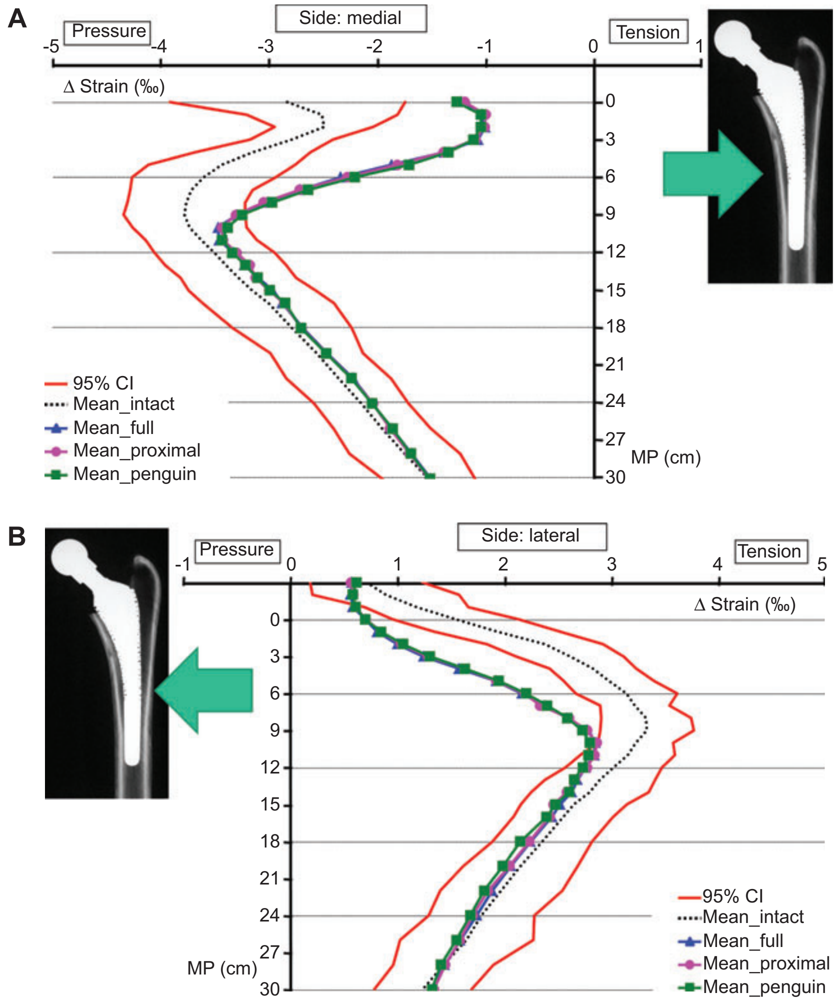

Figure 3 Strain measurement after implantation of the three hip stems (full, proximal, and penguin type).
Mean values are given for each type of hip stem (n=9) compared with the 95% CI and mean (mean_intact) for all nine intact composite femora. The radiograph corresponds to the position of the related measuring points. A significant strain reduction was observed after insertion of the hip stems at the proximal femur (MP 1–MP 9) on the medial (A) and lateral (B) sides.

conditions. The diaphyseal strain readings for the intact human femur medially (Figure 4) and laterally stayed within the 95% CI of the intact composite femora except for MP 2 medially and MP 1 laterally; proximo-medially (Figure 4) and proximo-anteriorly, a tendency toward higher compressive strains was observed. Proximo-laterally (MP 3–MP 6), lesser tensile strains occurred with the human femur as compared with the composite bones. In the posterior diaphyseal area, up to 50% lower tensile strains were noticed as compared with the composite femora.

Table 2 Cortical strain changes medially after implantation of the three different hip stems (n=9; mean value±1 standard deviation) as compared with the intact femora.

Height	Full	Proximal	Penguin
Medial side: compression strain changes±1 SD			
MP 1	-59%±14%	-60%±11%	-58%±13%
MP 3	-61%±12%	-60%±11%	-59%±8%
MP 6	-32%±8%	-34%±7%	-36%±8%
MP 9	-10%±7%	-10%±7%	-12%±6%
MP 12	-3%±6%	-4%±6%	-3%±6%

Strain values were obtained at the height of the trochanter minor (MP 1), the proximal (MP 3), middle (MP 6), distal third (MP 9), and the tip of the endoprostheses (MP 12).

Table 3 Cortical strain changes laterally after implantation of the three different hip stems (n=9; mean value±1 standard deviation) as compared with the intact femora.

Height	Full	Proximal	Penguin
Lateral side: tension strain changes±standard deviation			
MP 1	-52%±6%	-51%±8%	-50%±7%
MP 3	-50%±9%	-50%±10%	-48%±9%
MP 6	-30%±6%	-29%±4%	-29%±6%
MP 9	-15%±5%	-17%±4%	-17%±5%
MP 12	-6%±4%	-8%±2%	-7%±5%

Strain values were obtained at the height of the trochanter minor (MP 1), the proximal (MP 3), middle (MP 6), distal third (MP 9), and the tip of the endoprostheses (MP 12).

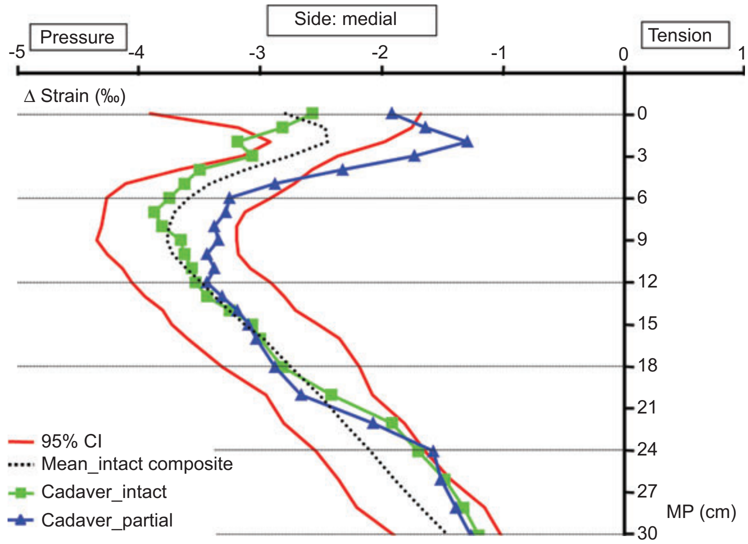

Figure 4 Results with the cadaver femur compared with the 95% CI and mean strain values of the intact composite femora (n=9). Strain pattern of the intact cadaver femur ("cadaver_intact") with a tendency toward higher compressive strains proximo-medially. Marked stress shielding after implantation of the partially coated hip stem ("cadaver_partial") at the proximal femur.

After implantation of the proximally coated hip stem, a stress shielding of 40% (MP 1, medially) and 42% (MP 1, laterally), respectively, was observed as compared with the intact cadaver femur. At the mid-stem height, there was an increase in tensile strains (+26% at MP 6) on the anterior side and a tendency toward lower compressive strains posteriorly.

Discussion

The main objective of this experimental study was to investigate the influence of the extent of porous coating of an anatomic hip stem on the femoral cortical strain pattern. The loading conditions of the femur are known to be an important factor for the periprosthetic remodeling process [15, 62] influencing the survival rate of the endoprosthetic implants and the incidence of thigh pain [1, 4, 37]. Cortical strain measurement does not provide direct information concerning the implant-bone interface conditions, which also influence the osteointegration of the implants [15, 33, 51]. As the long-term biological effects of pore size and surface structuring [26, 45] cannot be evaluated, the present study focuses on the effects of porous coating on cortical strain pattern in the early postoperative phase, which prepares the ground for later bone remodeling.

Major parts of the applied materials and methods of our study such as composite femora, standardized photoelastic coating, and a static loading model are validated by several studies [7, 9, 27, 57, 58]. In addition, the presented study deals with the influence of multiple uses of composite femora and a direct comparison with a human cadaver femur after implantation of the anatomic GHE hip stem. With reference to the frequently used simplified loading conditions [5, 6], our experimental setup comprises relevant forces and muscle straps [2, 8, 13]. These data have been confirmed by recent investigations [10]. Some authors recommend an additional simulation of the adductor muscles [8, 13], which have been realized within pilot tests with four composite femora. As we only found a locally limited reduction of bending stress, we refrained from attaching adductor straps in favor of leaving the photoelastic coating undamaged. Circumferential strains due to the press-fit implantation of cementless stems, so-called assembly strains, are also discussed to have some influence on photoelastic strain measurement after the insertion of a hip stem [21, 32]. It is doubted whether they are important for a setup with axial and torsional loading with regard to the viscoelasticity of the femora [49]. As principal strains can be corrected for assembly strains by knowing their magnitude and direction [21, 50], we conducted a strain measurement immediately after insertion of the endoprosthesis and after adjusting the experimental setup. The first measurement revealed assembly strains locally up to 18% of the strains of the loaded femora proximo-medially and proximo-anteriorly. The delayed repetition of the measurements showed decreased assembly strains down to 5% at individual measuring points. Following the recommendations of several authors, a correction for assembly strains was done for the measuring points [21, 46, 50].

The analysis of the implantation sequence (Table 1) showed no difference between the triplet groups. As there are no literature data available, it is concluded that the second-generation composite femora are appropriate for repeated measurements with geometrically identical GHE hip stems. This is supported by missing axial implant migration and the observation of undamaged polyurethane stock of the composite bones after the tests.

Localization and extent of medial/lateral stress shielding with all three implants (full, proximal and penguin type) corresponded well with the literature data of experimental studies with other hip stems. Zhou et al. registered a mean strain reduction of 65% (38%–88%) at the proximal femur with anatomic hip stems (Profile Hip, DePuy, Warsaw, IN, USA) [64]. Kim et al. reported a 36%–64% reduction of axial strains with different proximally coated anatomic hip stems at the height of the trochanter minor [36]. Even hip stems made of titanium alloys led to marked stress shielding in experimental studies with composite as well as cadaver bones. Otani et al. reported an 83%/89% (medial/lateral) strain reduction at the height of the trochanter minor [49]. Vail et al. reported 62%/30% (medial/lateral) stress shielding [61]. Our study revealed an increase in tensile strains on the anterior side and a tendency toward lower compressive strains posteriorly, which seems to be caused by the asymmetric design of the hip stem. These changes could not be proven to be significant. Hua and Walker inserted a symmetric and an asymmetric hip stem (experimental design) in photoelastically coated composite femora [30]. At the height of the antecurvation of the asymmetric stem, 48% higher strains were registered on the anterior side as compared with the intact femora. This effect was interpreted as a sign of a more direct load transfer and was absent with the symmetric stem [30]. Though partially structured stems aim for a proximal load transfer, whereas extensively coated implants should be integrated at their full length, the results of our study did not expose a significant difference in femoral cortical strain pattern within the three stems tested. Burgkart and Glisson implanted anatomic hip stems (fully and two-thirds proximally structured) with similar geometry and surface structure as the GHE hip stem in cadaver femora [5]. A tendency toward lesser stress shielding on the proximal-medial side was reported with the proximally coated implant compared with the fully coated implant. Though this experimental setup did not comply with all requirements for physiological conditions [2, 8, 10, 13], the use of cadaver femora instead of composite bones may influence the results of photoelastic tests with different surface structures. The polyurethane foam of the composite bones has a different porosity and is less compressible than the spongy bone of cadaver femora. These factors may limit the detection of differences that are only related to the surface structuring of implants that in other respects have the same geometry.

Using cadaver femora, the time-consuming preparation for photoelastic studies, the coating, and test series should be completed within 72 h [34, 54]. Some authors additionally aim to simulate osteointegration and implant fixation by bonding or cementation in their experimental studies [6, 64]. Only proximal fixation did not result in significant strain changes compared with the press-fit implantation, whereas a full-length bonding led to a significant stiffening of the system, enhancing stress shielding effects. However, the validity of these results for an *in vivo* situation is challenged [64]. The doubts are substantiated by radiological studies, which describe the periprosthetic bone density as locally variable and depending on the extent of porous coating and implant geometry [14, 25, 63] rather than homogeneously like glue or cement. Fully coated stems tend to cause a greater bone density reduction with more distal load transfer [14, 16, 22, 40, 63], which can even result in a failure of the stem [22]. Proximally coated stems induce bone condensation at the distal portion of the coated area [16, 22, 40, 48]. The influence of porous coating on bone remodeling is also investigated by several FE computational studies. With extensively coated anatomic stems, a higher stress shielding is calculated when assuming bone ingrowth [56]. However, stress shielding and predicted bone-mass alterations are even more influenced by stem length, material, distal geometry and the FE model assumptions made for the interface [20, 24, 48].

The present study revealed characteristic changes in cortical strain pattern after implantation of the cementless GHE hip stem in composite femora. These alterations in cortical loading were also found with the cadaver femur. However, the two other stems were not inserted due to considerable damage to the cancellous bone stock of the cadaver femur after removal of the proximally coated hip stem (GHE proximal). Alterations of the bone stock by sequential implantations in cadaver femora resulting in different stem positions have already been reported [46]. Our observations also correspond to clinical reports as well as the experience of the senior author (W.M.) about revisions of other implants with the Spongiosa Metal II surface. Even after migration or partial loosening, it may require a special equipment to disrupt the osseous interdigitation of femur and implant surface [31].

The high variability of the results of the discussed studies concerning the influence of the extent of porous coating on the biomechanics of the femur and the clinical/radiological outcome leads to the conclusion that the results should be considered as specific for each type of endoprosthesis. The major limitations of each study should also be regarded. The obtained results concerning the influence of the GHE hip stem on femoral cortical strain pattern are in good correspondence to the results of other studies with similar prostheses. We could not detect an influence of the extent of porous coating on femoral strain pattern assuming an early postoperative stage. This might change after osteointegration of the implant.

Looking particularly at the clinical results after THA with the GHE hip stem and its geometrically similar predecessors [Metal-cancellous cementless Lübeck (MCCL) and G2 stems], predominantly excellent results are reported [22, 23, 42, 63]. The implant survival rate was 96% after 8 years and 95% after 17 years [23]. Thigh pain was reported in 6% (fully coated, MCCL) [42] and 0% (proximally coated, G2), respectively [23], which is rather little compared with other cementless stems [1, 4, 11, 23, 42, 47]. Comparing the proximally coated and extensively coated MCCL stem, no significant differences with regard to the clinical scores were reported [63]. Bone mineral density was significantly greater in the distal-lateral and middle-medial periprosthetic regions with the fully porous-coated stem; no difference was found in the proximal two-thirds [63].

The presented biomechanical study could not reveal a significant difference between the three differently coated hip stems concerning their influence on femoral cortical strain pattern, assuming an immediate postoperative situation. However, with regard to the literature and clinical observations, the proximally coated or penguin-type GHE hip stem seems to be preferable to the extensively coated stem if clinical obstacles do not exist. This is supported by our experience of revision surgery of the fully coated GHE hip stem and its predecessors. Our knowledge concerning the biomechanics of the different types of surface coating of the GHE hip stem is aimed to be expanded by further cadaver studies.

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Conflict of interest statement

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