Photoelastic and Thermoelastic Measurement of Stress on the Proximal Femur Before and After Implantation of a Hip Prosthesis With Retention of the Femoral Neck

Hans Jürgen Refior, MD*
Christoph Schidlo, MD*
Wolfgang Plitz, PhD†
Sandro Heining, MD†

Abstract

This study demonstrated the improved medial support and the transfer of load onto the retained neck of the femur using seven fresh frozen femurs. Results confirm the reliability of the thermoelastic stress analysis method, which is comparable to the photoelastic surface coating method, but with greater sensitivity. The loading pattern after stem implantation shows a homogenous transfer of force onto the preserved femoral neck. After femoral neck removal, an inhomogeneous increase of the intertrochanteric compression loading was observed. Therefore, improved biomechanical conditions are created for a permanently stable implantation of stem prostheses with retention of the femoral neck.

In total hip endoprosthetic implantation, the head of the femur, including the neck, is usually removed. Earlier attempts at an alloarthroplastic treatment of coxarthrosis while retaining the femoral neck and head (e.g., with the Wagner cup) have not proved successful.1 In 1986, Freeman1 first described the advantages of femoral component implantation of the hip prosthesis while retaining the femoral neck: 1) the bone-free, varus-acting lever arm is reduced by a factor of three to four; 2) the resultant axially directed, vertical force is reduced through the improved bone support by a factor of two to three; 3) the rotational stability in the anteroposterior (AP) direction is distinctly raised; 4) in the event of a necessary change of prosthesis, the "second line of defense" is maintained through minimal bone resection; and 5) the anatomically determined antetorsion of the femoral neck is automatically reproduced in the implantation of the prosthesis, thus the biomechanics of the hip joint are less altered. Therefore, it can be assumed that femoral neck retention reduces the risk of prosthetic stem loosening.

The improved rotational stability obtained through femoral neck retention has been demonstrated in various biomechanical studies, especially with the use of longitudinally-structured cemented or cementless implants.2-5 In 1988, Carlson et al6 reported improved medial support. In their study, a pressure-sensitive film was placed between the prosthesis and medial base of a cadaveric femoral neck and a cementless stem prosthesis was implanted, with retention of the femoral neck and conventionally after its removal. Comparison of prosthesis implantation with femoral neck retention and removal demonstrated an increased pressure load on the base of the neck after applying an axial load to the femur in removal. The load uptake of the retained femoral neck was not investigated.

To demonstrate the improved medial support and load transfer onto the retained femoral neck, two in vitro methods for the measurement of stresses and strains on bone were used in this study: the photoelastic surface-coating method for stress measurement and thermoelastic stress analysis.

Materials and Methods

Five fresh individual femurs and one pair of femurs were obtained from male
cadavers aged between 23 and 42 years with healthy bone. In accordance with the criteria described in the literature,
the femurs were wrapped in cloths soaked in saline solution, sealed in polyethylene foil, and deep frozen at
−20°C. After thawing, soft tissue and periosteum were removed, and they were cemented in a metal socket in a
16° varus position by means of polymethylmethacrylate.

The strain pattern occurring naturally with the application of axial force was measured on the intact femur. For individual test steps, as well as determination of the size of the prosthesis by means of templates, true-to-scale AP radiographs were obtained with a 1.10-m film-focus distance (Figure 1). This was followed by removal of the femoral head and capping of the neck. A CLS Spotorno cementless stem prosthesis (Protek, Freiburg, Germany) was then implanted with retention of the femoral neck. As described by Albrektsson et al., a slot was cut into the femoral neck to implant the CLS-stem prosthesis. The strain pattern occurring on the surface of the bone with application of axial force was documented. After further measurements were taken, the femoral neck was removed at the base with retention of the prosthesis.

Five femurs, including the left femur of a pair, were investigated by means of photoelastic surface coating. As a comparison, the right femur of the pair and the remaining femur underwent thermoelastic stress analysis. For all measurements taken, only one axial loading was performed. Due to high costs, only two femurs were examined using thermoelastic stress analysis.

**Strain Analysis**

*Photoelastic Coating.* Milch and Pauwels introduced photoelastic measurement of stresses and strains on the three-dimensional bone model. Since the mid-1980s, photoelastic surface coated measurement of strains has been described by various authors as a quantitative and qualitative method for the two-dimensional measurement of the occurring surface strains and has been validated by means of strain gauges. Compared with point methods such as strain gauges, photoelastic measurement of strains is advantageous in that it represents the whole coated surface of the bone. As opposed to models of finite element analysis, it also takes into account changes due to the different shape, size, and age of bone.

After appropriate bone preparation, a 2-mm thick, PCI-photoelastic layer (Measurements Group, Raleigh, NC) was cast and later spread onto the proximal femur, in ventral to dorsal direction by PL1 adhesive (Measurements Group). A 030 reflection polariscope (Measurements Group) was used to measure the colored fringes appearing under loading (Figure 2). With this method, circular-polarized light passes through the photoelastic layer applied to the surface of the bone and is then reflected. As the light passes through the double refractive layer, the direction vector of the polarized light is altered according to the predominant strain state and appears as a color fringe after passing the analyzer. In this process, the isochromats correspond to areas of equal surface strains. Because no colored fringes were observed in the nonloaded state, the photoelastic layer was applied correctly and without autostress. After implantation of the cementless stem prosthesis, a new layer was applied to the bone because, in most cases, the coating is dislodged by implantation.

The transfer of force (without transverse force) was achieved by means of a polyethylene cup seated on ball-pads and corresponding with the ball-head. The static force was applied axially, stepwise in stages of 250 N, by a universal testing machine (Zwick model; Zwick, Ulm, Germany). Depending on the plasticity of the individual femurs, the maximum loading was between 2000 and 5000 N, which corresponds to three to seven times body weight during fast running and jumping. The colored fringes, appearing ventrally and dorsally, were photographed and subsequently evaluated.

The observed isochromat arrangements are proportional to the main difference of strains in the photoelastic layer applied, and thus to the surface of the test specimen. By means of an aluminium calibration strip coated in the manner described above, the strain (unit: μm/m) on the surface of the femur can thus be determined.21

*Thermoelastic Stress Analysis.* This method is based on the thermoelastic effect first described in 1830 by Weber and more extensively described in 1853 by Thomson. In the elastic field, a body exposed to dynamic loading to tensile or compressive stress undergoes a reversible transformation between mechanical and thermal forms of ener-
gy. If an adiabatic, elastic change in volume of the body under investigation is assumed, then the local change in temperature is proportional to the local change in stress and is valid for isotropic, homogeneous materials: 
\[ dT = -K_m \times T \times d(\text{d}T) \]  
where \( K_m \text{= thermoelastic constant, } T \text{= absolute body temperature, and } \text{d}T \text{= change in sum of principal stresses}. \]

The first measuring device for the thermoelastic analysis of stress, designated SPATE (Stress Pattern Analysis by Thermal Emission), was introduced in 1978 by Sira Ltd at the request of the British Admiralty to develop a radar antenna support. \(^{34-36}\) By means of a highly sensitive infrared camera, it measures the energy emitted from the surface due to the thermoelastic effect and subjects this energy to computer analysis. This procedure has proved successful in the optimization of structural components (e.g., in the automobile industry).

Initial experiences with the thermoelastic stress analysis on animal and human bone using the SPATE apparatus were reported by Duncan et al. \(^{37,38}\) Subsequently, this method of qualitative and semiquantitative measurement of stress on bone, which offered the advantage of integral assessment of complex geometric structures at high-resolution and without direct bone contact, was established. \(^{38,39}\) In 1995, Krüger-Franke et al. \(^{40}\) first compared the results of thermoelastic stress analysis on human bone with the strain-gauge method and demonstrated extensive qualitative and quantitative concordance between the two methods.

In the study of metal bodies, a surface coating similar to color is applied to improve the emission of heat. \(^{35,41}\) It was impossible to find a suitable color for bone. As a result, no further preparation of the bone under investigation is necessary, except for surface cleaning.

To compare changes in stresses obtained by means of photoelastic measurement, thermoelastic stress analysis was conducted on a right femur, after the corresponding left femur with a photoelastic coating had already been investigated. The first thermoelastic stress analysis was performed at the Research and Development Center of the automobile company, Bayerische Motoren Werke, in Munich, Germany, with theoretical and practical support in the handling of the SPATE 4000 apparatus (Ometron Ltd, London, England). Due to considerable costs, only one other study in the laboratory for biomechanics and experimental orthopaedics, within the framework of a demonstration of the SPATE 4000, has been performed (Figure 3).

The force was applied dynamically in the hydropulsator, with a mean load of 1150 ± 650 N and a frequency of 14 Hz. To achieve a high resolution, a 0.54-mm point-size was selected for the scanning infrared beam, with a 0.74-mm distance between the points. Each individual study was approximately 90 minutes, and was performed in each case in three stages in the anterior and posterior projections.

### Table 1: Photoelastic Coating Measurement and Calculation of the Maximum Microstrain Values of Intact Femurs

<table>
<thead>
<tr>
<th>Femur</th>
<th>Medial Femoral Neck</th>
<th>Intertrochanteric</th>
<th>Subtrochanteric</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>1550</td>
<td>425</td>
<td>1730</td>
</tr>
<tr>
<td>2†</td>
<td>1900</td>
<td>425</td>
<td>2230</td>
</tr>
<tr>
<td>3‡</td>
<td>1730</td>
<td>1160</td>
<td>1730</td>
</tr>
<tr>
<td>4‡</td>
<td>1550</td>
<td>570</td>
<td>950</td>
</tr>
<tr>
<td>5‡</td>
<td>1730</td>
<td>425</td>
<td>950</td>
</tr>
</tbody>
</table>

*Maximal femoral head force = 2000 N.  
†Maximal femoral head force = 4000 N.  
‡Maximal femoral head force = 3000 N.

### Results

#### Photoelastic-Coating Method

Within the framework of the tests, a homogeneous distribution of the colored fringes was similarly observed ventrally and dorsally on all intact femurs, with a maximum at the calcar femoral (i.e., in the sense of a pressure stress greatest at that point). Similarly, colored fringes were found on the lateral cortical layer due to the tensile stress (Figure 4) (Table 1).

Following prosthesis implantation with retention of the femoral neck, there was a homogeneous distribution of the occurring colored fringes similar to that on the intact femurs, with a clearly recognizable transfer of force.
onto the retained femoral neck (Figures 5 and 6). Because of the proximal anchorage mechanism of the cementless Spotorno prosthesis, an increase of the pressure stress occurred between the greater and lesser trochanter. Tensile stress on the lateral cortical layer could be detected as an indication only (Tables 2-4).

After removal of the femoral neck, increased intertrochanteric compression was observed. The inhomogenous distribution of the strain pattern was more noticeable than the absolute measured stress peaks below the trochanters. In addition, the medially situated maximum pressure shifted distally.

**Thermoelastic Stress Analysis**

With the relatively low, axial, dynamically applied mean load of 1150 N for both tests, a corresponding and almost identical distribution pattern of the total main stress levels was measured on the intact femurs and also after implantation of the prosthesis, compared to the stress distribution obtained with the photoelastic measurement. Comparison with the photoelastic measurement shows the improved medial support and homogeneous distribution of the stress lines observed with implantation of the prosthesis with femoral neck retention (Figure 7).

When performing thermoelastic stress analysis for the second time, the SPATE 4000 was updated with a charge coupled device camera. By means of photo scanning, this integrated camera obtains a three-dimensional representation of the surface relief of the body under investigation and the stress lines to be assigned (Figure 8).

The expected stiffening effect of the proximal femur also was noticeable after prosthesis implantation. Thus, in comparison to the intact femurs, approximately 50% stress reduction on the calcar femorale was recorded due to the decreased elasticity and the take-up of load by the implanted prosthesis. This reduction is similar to that described by Duncan and MacKenzie.

**DISCUSSION**

The test design used and described in this study corresponds to procedures documented in the literature. Aside from applying axial force, the test design, according to McLeish and Charnley, also simulates an abduct muscular traction on the greater trochanter. Heimkes et al. on the other hand, used anatomical–biomechanical investigations to demonstrate that instead of a tensile force on the greater trochanter there is pressure due to the fasciogluteal loop. In this simplified model, an additional simulation of individual muscular tractions is thus foregone—the complex biomechanics.

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**TABLE 2**

Maximal Microstrain Values at the Medial Femoral Neck After Implantation

<table>
<thead>
<tr>
<th>Femur</th>
<th>Microstrain (µm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1320</td>
</tr>
<tr>
<td>2</td>
<td>1800</td>
</tr>
<tr>
<td>3</td>
<td>1160</td>
</tr>
<tr>
<td>4</td>
<td>1320</td>
</tr>
<tr>
<td>5</td>
<td>1160</td>
</tr>
</tbody>
</table>

**TABLE 3**

Maximum Microstrain Values Before and After Neck Resection in the Intertrochanteric Region

<table>
<thead>
<tr>
<th>Femur</th>
<th>Microstrains (µm/m)</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1025</td>
<td>1160</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>570</td>
<td>1730</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1025</td>
<td>1160</td>
<td></td>
</tr>
<tr>
<td>4</td>
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</tr>
<tr>
<td>5</td>
<td>1025</td>
<td>1320</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 4**

Maximum Microstrain Values Before and After Neck Resection in the Subtrochanteric Region

<table>
<thead>
<tr>
<th>Femur</th>
<th>Microstrains (µm/m)</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1550</td>
<td>1160</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1320</td>
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<td>1550</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>950</td>
<td>1550</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>855</td>
<td>1160</td>
<td></td>
</tr>
</tbody>
</table>
of the hip joint can never be simulated by such means. The 16° valgus position of the femur selected in the present study corresponds to the resultant force on the hip in the vector parallelogram according to Pauwels' and lies midway in the range of angles (between 10° and 25°) used by other authors.13,15,16,19,43,46,50-52

The method used for the qualitative and quantitative measurement of the stresses and strains on the proximal femur by means of photoelastic coating is a proven and validated procedure. However, it is a time-consuming preparation and difficult quantitative evaluation.11-13,43,53,54

The use of thermoelastic stress analysis on human bone, which has not been widely described, provides a qualitative result comparable to the photoelastic-coating method for the measurement of stresses, but with far greater susceptibility. Depending on the size of the field to be studied and the resolution required, the disadvantages lie in the relatively long test procedure. At the same time, to avoid signs of drying out, the bone should be kept moist between the different measurement procedures. Quantitative analysis by means of thermoelastic stress analysis is associated with considerable difficulties: it requires the E-modulus of the bone to be known, however, this is only an approximate determination, not exact. 39,40,55-60

In contrast to the methods of measurement such as the strain-gauge method14-16,61-63 and finite elemental calculation,17,18,58,64-66 both procedures enable extensive presentation of complex geometric structures.67

The forces acting on the total hip joint endoprosthesis have been described by Bergmann et al.19 and the importance of the rotational forces emphasized. Several experimental studies demonstrated the improved rotational stability obtained with the implantation of prostheses with retention of the femoral neck.2,3,4,15 However, in the present measurements, the effect of the rotational forces on the femoral neck and the coxal end of the femur were not investigated. Based on the literature, it must, however, be presumed that with implantation of a stem prosthesis, the retained femoral neck is important for the rotational stability of the implant. The loading pattern following axial force application on the intact femur with medial pressure loading and lateral tensile loading, as presented herein, is consistent with the data in the literature.15,43-45,51,52,64,66,68-70

The homogeneous transfer of force of the prosthesis on the femoral neck after stem implantation with retention of the femoral neck has not been demonstrated in the literature. After removal of the femoral neck, an increase of the intertrochanteric compression loading and an inhomogeneous distribution pattern below the trochanters were observed. The changes described could be demonstrated by means of both photoelastic-coating measurement and thermoelastic stress analysis.

Furthermore, the results presented confirm the study by Carlson et al.6 in which an increase of the compression loading on the medial base of the femoral neck was observed after its removal. Regarding the clinical situation in recent years, the first clinical studies report good to very good short-term results after stem implantation of cementless hip endoprostheses with retention of the femoral neck.8,71,72

Long-term results and comparative studies are not yet available.

In the studies discussed, cementless implants from various manufacturers were used. The surgical procedures also differed accordingly. For example, Pipino and Calderale72 retain the circumference of the femoral neck in that they use a relatively short, curved prosthesis. Albrektsson et al.8 Krackow et al.71 and White et al. cut a slot in the femoral neck to implant the graduated stem prostheses they use. In the studies presented herein, the same procedure was followed. In contrast to the short-stemmed implant used by Pipino and Calderale,72 it is impossible to maintain the circumference of the femoral neck with intramedullary, long-stemmed anchorage of the stem. Resultant changes in compression distribution require further investigation.

**CONCLUSION**

The distribution pattern following removal of the femoral neck close to its base results in less favorable biomechanical conditions in increased inter-
trochanteric and mediolateral loading, and thus probably represents an increased risk of stem loosening. Long-term clinical results are needed to prove the advantages of hip prosthesis implantation with retention of the femoral neck. However, based on our results, improved biomechanical conditions are more likely created for the permanently stable implantation of stem prostheses with retention of the femoral neck. Further experimental studies should, however, broaden the theoretical basis and create the basic conditions for appropriate clinical application.

REFERENCES


