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TRAUMA

The role of inter-prosthetic distance, cortical thickness and bone mineral density in the development of inter-prosthetic fractures of the femur

A BIOMECHANICAL CADAVER STUDY

It is becoming increasingly common for a patient to have ipsilateral hip and knee replacements. The inter-prosthetic (IP) distance, the distance between the tips of hip and knee prostheses, has been thought to be associated with an increased risk of IP fracture. Small gap distances are generally assumed to act as stress risers, although there is no real biomechanical evidence to support this.

The purpose of this study was to evaluate the influence of IP distance, cortical thickness and bone mineral density on the likelihood of an IP femoral fracture.

A total of 18 human femur specimens were randomised into three groups by bone density and cortical thickness. For each group, a defined IP distance of 35 mm, 80 mm or 160 mm was created by choosing the appropriate lengths of component. The maximum fracture strength was determined using a four-point bending test.

The fracture force of all three groups was similar (p = 0.498). There was a highly significant correlation between the cortical area and the fracture strength (r = 0.804, p < 0.001), whereas bone density showed no influence.

This study suggests that the IP distance has little influence on fracture strength in IP femoral fractures: the thickness of the cortex seems to be the decisive factor.

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The total number of hip and knee replacements (THR, TKR) undertaken continues to rise. This can be explained, in part, by an aging population and the increasing physical demands and expectations of the older patient. It follows that complications associated with joint replacement have also increased significantly.¹ Furthermore, patients who have undergone a THR and TKR in the same leg are also increasing in number as are fractures associated with them. Patients with ipsilateral hip and knee replacements are at risk not only of peri-prosthetic fracture but also of fracture between the implants, so-called inter-prosthetic (IP) fracture. The incidence of these fractures is unknown. Kenny et al² described four cases in a series of 320 patients with ipsilateral hip and knee prostheses, an incidence of 1.25%. Sah et al³ saw 22 patients with IP fractures between well-fixed THR and TKRs in two hospitals between 2002 and 2006. Other authors have described 13 cases within six years⁴ and 24 cases within 16 years of the study period.⁵

Consequently, the question arises as to whether the distance between a stemmed hip and knee implant is an important factor in the development of an inter-prosthetic fracture of the femur.

It has been shown that the normal structural and mechanical properties of the femur change when a femoral stem is implanted: this causes a reduction in strength (load to failure) of the femur of approximately 32%.⁶ Implantation of a stemmed component in the distal femur can be expected to further reduce its strength.

Lehmann et al⁷ showed that, in a patient with a THR, the insertion of a retrograde femoral nail results in a high stress riser between the tip of the nail and the tip of the stem. The implantation of a well-fixed constrained knee prosthesis does not increase the risk of fracture.⁷ The influence of the IP distance on the risk of fracture is unknown. In the absence of biomechanical evidence, there is concern that a short distance between the tips of two stemmed implants in the same femur may predispose to fracture. Contrary to this



Fig. 1

QCT measurements. Cross-sections of the condylar region and the femoral diaphysis. Length of the femur from the tip of the greater trochanter to the end of the condyles (red line) and middle of the diaphysis (lilac line).

hypothesis, a study by Iesaka et al⁸ suggests that the distance between two well-fixed stems has only a minor influence on the development of an IP fracture. In a finite element model Soenen et al⁹ have shown that a critical loading condition, such as falling on an object, increases the risk of IP fracture, as the distance between the two prostheses decreases.

As life expectancy increases, the frequency of revision surgery of the hip and knee is also increasing.¹⁰ It is therefore likely that implants with longer stems will be used more frequently and patients with ipsilateral hip and knee implants and revision stems will become increasingly common. The distance between the tips of prostheses (IP distance) will vary and some may be associated with an increased risk of fracture.

The aim of this biomechanical cadaver study was to evaluate the influence of the IP distance, bone mineral density (BMD) and cortical thickness on the likelihood of an inter-prosthetic fracture of the femur. Our hypothesis was that the IP distance does not influence the likelihood of IP femoral fracture, whereas the bone density and the cortical thickness are more likely to be causal.

Materials and Methods

Approval for this study was granted by the local ethics committee of the state of Hamburg, Germany.

Specimens. A total of 18 femora were collected from 11 human cadavers (three female, eight male) with a mean age of 62.4 years (50 to 73; SD 8.5). Since IP fractures are often associated with osteoporosis, specimens were collected from donors with expected osteoporotic bone mass. Each specimen was removed at the local Institute of Forensic Medicine, stored at -20 C° directly after dissection and



Fia. 2

Measurement of the cortical thickness A (red line) and cortical area B (red area) in the middle of the diaphysis.

thawed overnight prior to biomechanical testing. All femora were randomised on the basis of BMD estimated by quantitative computed tomography (QCT) and matched by bone mineral density as in previous biomechanical studies.^{6,7,11-13}

QCT measurements. Each femur was scanned using a 16row CT-scanner (Brilliance 16 CT; Philips Healthcare, Hamburg, Germany) and a solid calibration phantom (Bone Density Calibration Phantom; QRM, Moehrendorf, Germany). The scan parameters were 120 kVp; 50 mA; constant table height and 1 mm slice thickness. The QCT scans were analysed with the 3D Analysis Software Avizo 5.1 (VSG Inc., Burlington, Massachussetts). The integral volumetric BMD (vBMD) as the quotient of bone mineral content and bone volume was determined in the transverse plane of the condyles and in the middle of the diaphysis (Fig. 1). The length of the femur was defined as the distance between the tip of the greater trochanter and the distal end of the condyles. The total cross-sectional area for BMD measurement was defined as the area enclosed within the outer border of the compact bone in the transverse plane. Additional evaluation of the cortical thickness and cortical area was conducted by measuring the thickness of the cortex directly opposite the linea aspera and the crosssectional area of the compact bone in the middle of the diaphysis (Fig. 2). The total cross-sectional area of the femur was separated into cortex, sub-cortex and marrow cavity based on a separation threshold of 710 mg/cm³. The mean value of the vBMD for the diaphysis was 801 mg/cm³ (696 to 947; SD 66) and for the condylar region 183 mg/cm³ (132 to 247; SD 29). The threshold for specimens to be considered osteoporotic was defined as a vBMD lower than 1000 mg/cm³ at the diaphysis.^{6,11} The mean cortical



All femoral were randomised on the basis of QCT-data into three groups. There was no statistical significance between a) the bone mineral density (BMD) and b) the cortical thickness of the groups.



Fig. 4

Control anteroposterior radiographs of the femur with a metal rod of defined length for each group. Group I: 35 mm inter-prosthetic (IP) distance; Group II 80 mm IP distance; Group III 160 mm IP distance.

thickness in the middle of the diaphysis for all specimens was 5.1 mm (3.6 to 6.0; SD 0.63) and the mean cross-sectional area of the cortex 527.1 mm² (417 to 676; SD 78). The femora were divided into three groups for comparison (Fig. 3).

The influence of IP distance on the development of an IP femoral fracture was investigated for three different gap sizes; 35 mm (Group 1), 80 mm (Group 2) and 160 mm (Group 3). The IP distance was defined as the distance between the distal tip of the femoral stem and the proximal tip of the femoral component of the TKR.

After thawing the fresh-frozen specimens, all soft -tissue was removed and the medullary canals were prepared for implantation of the prostheses. A cemented Lubinus Classic Plus hip prosthesis (Link, Hamburg, Germany) and cemented modular total knee prosthesis Endo-Modell M (Link) of different stem lengths were used. The appropriate size of stem was determined from the CT scans. In addition to the different stem lengths of the knee prostheses, the resection level was adjusted to achieve as exact an IP distance as possible. The Optipac system with Refobacin R bone cement (Biomet Inc., Warsaw, Indiana) was used for cementation. A cement restrictor with a radiological marker (PE cement restrictor, Smith & Nephew, Memphis, Tennessee) was implanted 10 mm distal or proximal to the tip of each prosthesis. In the group with an IP distance of 35 mm only one cement restrictor was used in order to create the shortest possible distance with 10 mm distance to the tip of each prosthesis for a restrictor length of 15 mm. Radiographs were taken before and after each step to ensure that the correct distance between the prostheses, satisfactory implantation of the cement restrictor and prosthesis and adequate cementation of the prosthesis. The





Biomechanical test set-up. A servo-hydraulic testing machine was used (MTS 858.2, MTS Systems, Eden Prairie, Minnesota). The femur was loaded with a constant bending moment between the inner supports. I₁: distance between the outer supports; I₂: distance between the inner supports; F: applied force; M: bending moment

$$M = \frac{F}{2} * \frac{l_1 - l_2}{2}; l = \frac{l_1 - l_2}{2} = 8 \ cm$$

Fig. 6

Equation 1. I_1 : distance between the outer supports; I_2 : distance between the inner supports; F: applied force; I: lever arm length.

distances were checked using a radiological ruler and metal rod of a defined length for each planned distance (Fig. 4). Since it is not possible to simulate osseous ingrowth of prosthesis in a laboratory setting, uncemented stems were not included.¹⁴

Four-point bending test. The four-point bending test applies a constant moment throughout the entire femur, which means that the moment is the same between the inner supports of the testing machine, while it increases with increasing load. Furthermore, it omits transverse force. Previous studies have shown that this loading condition is suitable to create an IP fracture.⁶ A servo-hydraulic testing machine (MTS 858.2, MTS Systems, Eden Praire, Minnesota) was used for testing. After implantation of both prostheses, the femora were embedded in aluminum pots at their proximal and distal ends using polyurethane (Ureol FC 53, Gößl & Pfaff, Karlskron, Germany). They were then placed on the outer two supports and loaded with a constant bending moment between the middle two supports according to equation 1 (Figs 5 and 6).

Load was applied with a constant speed of 0.1 mm/s until fracture occurred.



Fig. 7

Tested specimens with an inter-prosthetic fracture (proximal femur on the left side of the picture). A: 35 mm inter-prosthetic gap distance, B: 80 mm inter-prosthetic gap distance, C 160 mm inter-prosthetic gap distance.

Statistics

Statistical evaluation was undertaken using the software package IBM SPSS Statistics 21 (IBM, Armonk, New York). Data were shown to be normally distributed for each tested parameter using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Even so, parametric statistical tests are not generally conclusive for small sample sizes. The homogeneity of variance between the groups was controlled using the Levene test. Given the sample size, parametric (one-way analysis of variance (ANOVA)) and

		BMD Condylar Region (mg/cm³)		BMD Diaphysi	is (mg/cm³)	Cortical thickness (mm)		Cortical area (mm²)		F max (N)		Max bending moment (Nm)	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Group I (mm)	35	164	132 to 208	799.62	734 to 947	4.74	3.61 to 5.76	483	419 to 575	10681	5832 to 14387	427	233 to 575
Group II	80	192	172 to 223	803.3	696 to 908	5.09	4.34 to 5.7	538	416 to 633	12601	8655 to 15980	504	346 to 597
Group III	160	193	158 to 246	798.72	724 to 859	5.54	5.2 to 6.01	561	498 to 676	11804	10026 to 15750	472	401 to 630







Fig. 9

Box plot of all groups showing the forces needed to create a fracture. There was no statistical significance between the groups.

Correlation between the cross-sectional area of the cortex measured in the middle of the diaphysis and the fracture strength for each specimen.

nonparametric (Kruskal-Wallis test) analyses were performed to verify the homogeneity of BMD and cortical thickness as well as to compare the results between the groups.

A multiple regression analysis was conducted to show the influence of the BMD at the diaphysis, the BMD at the condylar region, cortical thickness and cortical area on fracture strength. The type I error probability was set to $\alpha = 0.05$ for all tests.

Results

There were no significant differences between the groups in the BMD of the condylar region (p = 0.169, one-way ANOVA), the BMD of the diaphysis (p = 0.993, one-way ANOVA), cortical thickness (p = 0.081, one-way ANOVA) or cortical area (p = 0.216, one-way ANOVA (Fig. 3)).

In all tested femora, an IP fracture occurred between the two implants and the implants remained well fixed to the bone (Fig. 7).

Group I, with an IP distance of 35 mm, showed a mean fracture strength of 10681 N (5832 to 14387; SD 3032).

The fracture occurred at the tip of one or other implant. Group II (80 mm) showed a mean fracture strength of 12601 N (8655 to 15980; SD 2992). In this group the bone fractured at the proximal end of the knee prosthesis in every case. Group III (160 mm) showed a mean fracture strength of 11804 N (10026 TO 15750; SD 2188). Once again, every fracture occurred at the proximal end of the knee prosthesis. Group I showed a mean maximum bending moment of 427 Nm (233 TO 575; SD 121), Group II 504 Nm (346 to 597; SD 119) and Group III 472 Nm (401 to 630; SD 87) (Table I). There was no statistically significant difference between the mean fracture strength and consequently between the mean maximum bending moment in any of the three groups (p = 0.548, Kruskal–Wallis test) (Fig. 8).

A multiple regression analysis showed that the BMD measured in the condylar region and at the diaphysis had no significant effect on fracture strength (BMD condylar region: r = 0.299; p = 0.228; BMD diaphysis: r = -0.142; p = 0.573). By contrast, there was a highly significant correlation between cortical thickness (r = 0.688; p = 0.001)

and the cross-sectional area of the cortex (r = 0.804; p < 0.001) measured in the middle of the diaphysis and fracture strength (Fig. 9). The positive correlation coefficient indicates that the fracture resistance increases with increasing cortical thickness / area. This explains the slightly lower force to failure in the group with an IP gap of 35 mm, which was the group with the lowest cortical thickness and area (Fig. 3).

Discussion

IP fracture of the femur is increasing in frequency and can be difficult to treat.¹⁵

Although there have been almost no studies on this topic, it has been speculated that a short IP distance between a stemmed hip and knee prosthesis acts as a stress riser and may predispose to the development of an IP fracture.^{16,17} Some authors have suggested that distances below 6 cm or less than two widths of the diaphysis are critical in clinical practice.¹⁸

Contrary to these assumptions, our results clearly show that the IP distance has no significant influence on fracture strength in IP fractures of the femur. Furthermore, the cortical thickness and especially the cortical area, correlates significantly with load to failure. These results are consistent with the finite-element study of Iesaka et al,⁸ which shows that the distance between the two stems does not affect peak tensile stress and that cortical thickness is an important variable affecting stress on the femur.

The location of the fractures shows that the bone between the two prostheses is the weakest section of the construct. The stiffness of the parts containing the cemented prosthesis is higher than the stiffness of the bone itself, so that the greatest difference in stiffness is at the tips of the prostheses. These are exactly the points at which the femur always fractured during testing, regardless of whether the IP distance was short or long.

No correlation was found between the BMD of either the diaphysis or the condylar region and fracture strength. Thus, the BMD of the diaphysis cannot be used to make a prediction about fracture resistance. This could be due to the near total lack of trabecular bone in the diaphysis. Therefore, the integral volumetric BMD is almost exclusively determined by the cortex, which does not seem to be a predictive factor. Bousson et al¹⁹ has shown that there is no significant difference between the integral shaft BMD between a control group and patients who suffer a hip fracture, but in fact there is significant difference between these groups; a result that also underlines our findings about cortical thicknesses.

Our results also show an increasing force to fracture as the IP gap distance increases. The minimum fracture force of the 160 mm group is almost twice that of the 35 mm group. This, however, is due to the different thickness of the cortices and not to the different IP distances (Fig. 8). Nevertheless, further studies to investigate varying IP distances in bone with similar cortical thicknesses or standardised IP distances with varying cortical thicknesses could provide further information to support our results.

Our results which have not shown any correlation between inter-prosthetic distance and fracture risk are at variance with the Finite Element Analysis of Soenen et al.9 These authors found an increasing strain and fracture risk between two stemmed implants in a similar four point bending test.9 Our results clearly show the significance of cortical thickness, which was not considered in their finite element study. Even if the strain increases with decreasing IP distance, the growing cortical thickness from the metaphysis to the middle of the diaphysis seems to be able to absorb this rising tension and the fracture force does not make any difference. Furthermore, this would reinforce the results of the groups with larger distances (80 mm and 160 mm), where the cortical bone might be expected to be thinner as the stem tips are closer to the metaphysis, but the fracture force shows no significant difference in comparison to the other groups.

Our results suggest that in revision surgery, in which long stem implants are used, a short distance between the tips of the stems is of little importance to the longer-term risk of IP fracture and that cortical thickness is more significant. It seems that the tip of any implant should be located in a region with a sufficient thickness of cortex. Thus selection of the implant should be based on the mode of fixation of the implant and femoral morphology, rather than on the prospective interprosthetic distance.

There are some limitations of this study. A biomechanical cadaver model is not able to simulate *in vivo* conditions as the contribution of muscles or ligaments to the bending strength is neglected. The four-point bending model with a force acting from lateral to medial considers only a few mechanisms of injury e.g. a side-on impact. On the other hand, and in contrast to a three-point bending test where the force acts at a central support, it produces a constant bending moment between the inner supports and is able to generate an IP fracture under laboratory conditions.

Loosening of a prosthesis was not considered in our cadaver model since we used freshly cemented prostheses. Therefore, the influence of a loose stem, which may act as a major stress riser for an IP fracture, cannot be commented upon. It could be hypothesised that a loose stem leads to destruction of the endosteum at the tip of a stem and therefore, the cortex is weakened between the implants leading to high local stresses.⁷ We did not investigate the effect of a reversal of implant length ratio (longer knee then hip stem). This situation might give slightly different results due to the different positions of the tips of the implants in relation to the changing cortical thickness of the femur. Furthermore, this study concentrated solely on the risk of fracture and cannot provide any information about the clinical effects of different IP distances and fractures *in vivo*.

In summary, we conclude that, in our experimental model, the inter-prosthetic distance does not have a

significant effect on the risk of developing an IP fracture of the femur. Furthermore, cortical thickness is a predictive factor, unlike bone mineral density.

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