

Mechanical torque measurement in the proximal femur correlates to failure load and bone mineral density *ex vivo*

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Abstract

Knowledge of local bone quality is essential for surgeons to determine operation techniques. A device for intraoperative measurement of local bone quality has been developed by the AO-Research Foundation (DensiProbe®). We used this device to experimentally measure peak breakaway torque of trabecular bone in the proximal femur and correlated this with local bone mineral density (BMD) and failure load. Bone mineral density of 160 cadaver femurs was measured by *ex situ* dual-energy X-ray absorptiometry. The failure load of all femurs was analyzed by side-impact analysis. Femur fractures were fixed and mechanical peak torque was measured with the DensiProbe® device. Correlation was calculated whereas correlation coefficient and significance was calculated by Fisher's Z-transformation. Moreover, linear regression analysis was carried out. The unpaired Student's t-test was used to assess the significance of differences. The Ward triangle region had the lowest BMD with 0.511 g/cm² (±0.17 g/cm²), followed by the upper neck region with 0.546 g/cm² (±0.16 g/cm²), trochanteric region with 0.685 g/cm² (±0.19 g/cm²) and the femoral neck with 0.813 g/cm² (±0.2 g/cm²). Peak torque of DensiProbe® in the femoral head was 3.48 Nm (±2.34 Nm). Load to failure was 4050.2 N (±1586.7 N). The highest correlation of peak torque measured by Densi Probe® and load to failure was found in the femoral neck (r=0.64, P<0.001). The overall correlation of mechanical peak torque with T-score was r=0.60 (P<0.001). A correlation was found between mechanical peak torque, load to failure of bone and BMD *in vitro*. Trabecular strength of bone and bone mineral density are different aspects of bone strength, but a correlation was found between them. Mechanical

peak torque as measured may contribute additional information about bone strength, especially in the perioperative testing.

Introduction

Osteoporotic fractures are one of the leading health concerns worldwide, and fractures of the hip as a result of fragility are particularly associated with increased mortality, disability and reduced Quality of Life.^{1,2}

Patients with hip fractures, therefore, require sufficient fixation to allow immediate load bearing and mobilization in order to reduce associated co-morbidity. However, stability of a fracture fixation depends on bone quality, fracture type, position of the implant, and the reduction achieved.^{3,4} Orthopedic surgeons are not able to influence the type of fracture and the quality of bone, but they may influence the degree of reduction and the position of the implant during fixation. Analysis of the type of fracture, the position of the implant, and the best implant to choose, is worked out as a constant ongoing process.

One aspect of bone quality is the bone mineral density (BMD) that represents the mineral content of the bone. Even if bone structure or strength of trabecular and cortical bone is not addressed, BMD can be assessed by dual-energy X-ray absorptiometry (DXA) or quantitative computed tomography (QCT). There is concern about osteoporosis being a single and independent risk factor for failure of an implant, even though implant position and reduction are correct.^{5,6} Site-specific assessment of BMD can accurately predict the quality of bone to analyze the fracture or develop new implants.^{7,8} Moreover, topological analysis of mineral distribution in scan images improves prediction of fracture or non-fracture, as recently shown.⁹

Unfortunately, these diagnostic tools are often unavailable before or during an operation, thus anchorage of an implant or possible failure of osteosynthesis can not really be estimated by the orthopedic surgeon before surgery. To predict the strength of the bone, and, therefore, the likelihood of an implant failure, the AO Research Institute (AO-Foundation, Davos, Switzerland) has developed a mechanical torque-testing device for intraoperative measurement, the DensiProbe®.^{10,11} The first results, presented by Suhm *et al.*, showed a significant correlation of peak torque with BMD (r²=0.814) and a significant correlation with implant cut-out (r=0.795) in 16 human cadaveric femoral bones.

Perioperative knowledge of bone strength could help the orthopedic surgeon to decide which is the better option: augmentation of osteosynthesis with cement or implantation of

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an arthroplasty.^{12,13} Bone strength still needs to be estimated and a correlation made between bone density as defined by BMD to the mechanical qualities of the bone.

In the present experimental study, we analyzed the mechanical peak torque in the femoral head, the BMD in different regions of the proximal femur, and the load to failure of human femur bone *in vitro*. Our intention was to correlate the mechanical qualities of bone to the BMD.

Materials and Methods

Specimens of bone

A total of 160 cadaveric femurs from the years 1998-2004 were obtained from the Anatomical Institute of the University of Munich, Germany. All patients had given written consent for scientific analysis before death. Storage conditions of each femur were similar throughout the period. Initially, the cadavers were fixed in formalin by intra-arterial injection, and stored in closed containers covered with formalin before and after analysis. All femurs had been embalmed for a mean

4.5 years (range 3-8) before they were tested. The bone and adjacent joints showed no macroscopic disease such as fracture, tumor, general bone disease, or severe osteoarthritis.

Measurement of bone mineral density

Bone density was measured by DXA with the GE Lunar Prodigy Scanner (GE Lunar Corporation, Madison, Wisconsin, USA). To simulate soft tissue, the bones were kept under water, since has been proven to have similar absorption to soft tissue.^{14,15} The automatic analysis of bone mineral content [BMC (g)] was used to calculate the BMD (g/cm^2) of different regions of interest, such as the femoral neck, the Ward triangle, the trochanteric region, and the whole femur. The T-score is the number of SDs above or below the mean BMD for a healthy 25-year old adult of the same sex and ethnicity.

Measurement of load to failure

Failure load of the femurs was tested by side-impact analysis, as described by Eckstein *et al.*, with a universal testing machine (Zwick 1445 Ulm, Germany).¹⁵ All bones were fixed in a defined position, so breakage on controlled load bearing was recorded. Maximal recorded load was defined as the failure load of bone (Figure 1).

Measurement of mechanical torque

All fractured femoral bones were anatomically reduced before mechanical testing. The

fractures were, therefore, fixed with a bandage and embalmed with cement for correct alignment. Femoral necks were vertically adjusted, and the distance to the apex of the bone was measured before cementing (Figure 2). The distance to the apex in the vertical position of the cemented construct corresponded to the femoral neck and the drilling direction of the universal testing machine. The cortex was then drilled and a 2.5 mm Kirschner (K) wire was pushed forward by the universal testing machine (Zwick 1445 Ulm, Germany) vertically into the middle of the bone near to the top of the apex. During this, the force of pushing forward the K-wire was recorded in 0.1s as a force/distance analysis. Then the DensiProbe® testing device, as described by Suhm *et al.* was inserted.¹⁰ The DensiProbe® was pushed as far as 15 mm of the apex where the mechanical torque was measured and recorded by the testing device. The DensiProbe® device records the mechanical force of the wings of the instrument to break away the trabecular bone in this region (Figure 3). The DensiProbe® device has an outer diameter of 7 mm and the blade at the apex has a length of 25 mm. Data of the instrument were read out by computer analysis.

Statistical analysis

For statistical analysis we used Statview 4.5 (Abacus Concepts, Berkeley, California, USA). Correlation was analyzed from linear regression analysis. We used Fisher's Z transforma-

tion to calculate the correlation coefficient and assess the significance of differences. The correlations were shown graphically with bivariate scattergrams and regression analysis. The significance of differences between men and women was assessed using the unpaired Student's t-test.

Results

A total of 160 cadaveric femurs comprising 90 male and 70 female bones, mean age 79.6 years (± 10.3 years) were included in this analysis. Mean age of male bones was 77.5 years (± 10.8 years) whereas mean age of female bones was 82.2 years (± 9 years).

Table 1 shows the basic data and gender differences of the variables studied. The highest BMD was found in the femoral neck with $0.813 \text{ g}/\text{cm}^2$ ($\pm 0.20 \text{ g}/\text{cm}^2$). In the trochanter region, BMD was $0.69 \text{ g}/\text{cm}^2$ ($\pm 0.19 \text{ g}/\text{cm}^2$), BMD in the upper neck region was $0.55 \text{ g}/\text{cm}^2$ ($\pm 0.16 \text{ g}/\text{cm}^2$), and $0.51 \text{ g}/\text{cm}^2$ ($\pm 0.17 \text{ g}/\text{cm}^2$) in the Ward's triangle. Men had significantly higher BMD in all regions of interest in the proximal femur. T-scores were 44.6% lower among women. All gender differences were significant ($P < 0.001$).

Mean mechanical peak torque measured with the DensiProbe® device 15 mm below the surface of the femoral head was 3.48 Nm (± 2.34 Nm). The peak torque was 4.41 Nm (± 2.32 Nm) in male bone and 2.26 Nm (± 1.74 Nm) in female bone ($P < 0.001$). The peak torque in male bone was, therefore, double that in female bone. After drilling the cortex, the power of pushing forward the K-wire to the

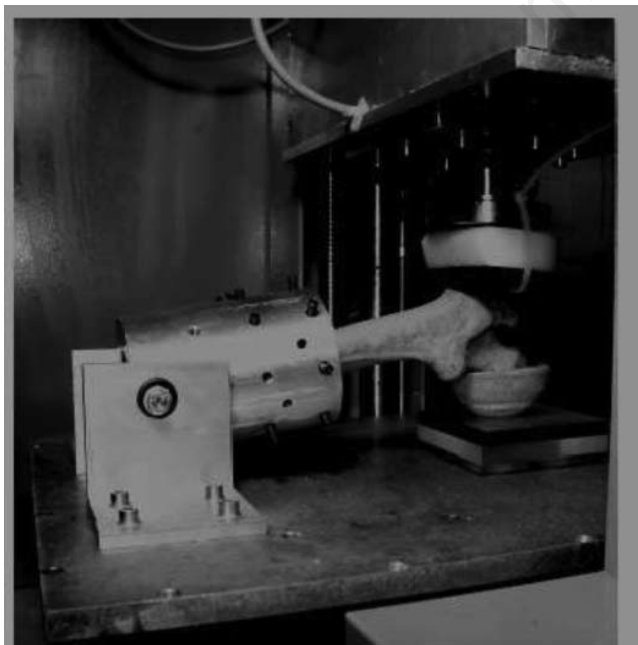


Figure 1. Failure load tested by side-impact analysis with a universal testing machine (Zwick 1445 Ulm, Germany). Reprinted with permission of Eckstein *et al.*¹⁵

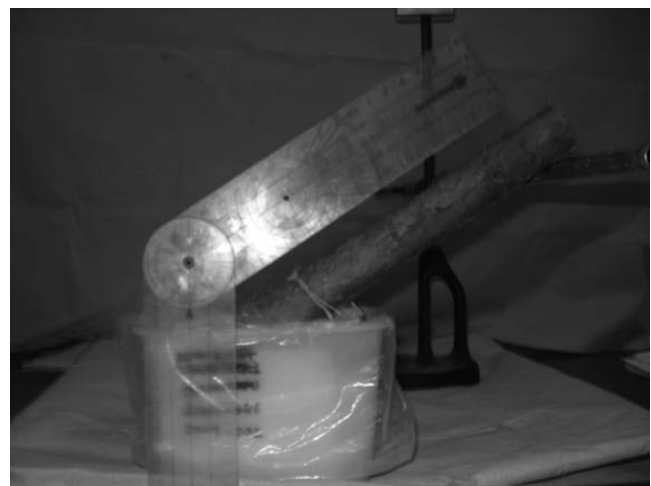


Figure 2. Vertical alignment of the femoral neck and cement fixation technique of the proximal femur.

top of the femoral head was 997.5 N (± 592.4 N): 1228 N (± 609 N) in males and 710.6 N (± 426.6 N) in females.

Load to failure of the proximal femoral bone measured by side-impact analysis was 4052 N (± 1587 N). In total, male bone showed a failure load of 4866 N (± 1447.6) and female bone of 2991 (± 1045 N).

There was no correlation between the torque resistance and time of storage of the probes, even when differences in storage time (range 3-8 years) were compared.

Correlations of mechanical torque

Mechanical peak torque measurement correlated with the failure load of bone measured by side-impact analysis ($r=0.62$; $P<0.001$). Only a weak correlation was found between mechanical torque and T-score ($r=0.602$). The best correlation of mechanical peak torque and BMD in the femoral neck was assessed at $r=0.64$ ($P<0.001$). In the different regions of the proximal femur, the BMD and QCT measurements correlated well with failure load (from $r=0.79$ femoral neck up to $r=0.798$ upper femoral neck) (Table 2). However, a good correlation was found when the T-score was compared with the failure load of bone ($r=0.743$;

$P<0.001$). Overall, correlation of the T-score and QCT with failure load was superior to correlations of mechanical torque and failure load. We could prove that the T-score was defined mainly by the BMD in the femoral neck (g/cm^2) with a correlation of $r=0.985$.

Linear regression analysis of mechanical torque and failure load shows a sex-related correlation between mechanical peak torque and failure load of femoral bone (Figure 4).

Discussion

We analyzed a large cohort of human femoral bone to correlate its mechanical properties, breakaway strength of trabecular bone and failure load of bone, measured by side-impact analysis, with BMD *in vitro*. To our knowledge, this is the first study to report the extent of gender differences of mechanical torque, failure load and BMD. We did not analyze force of implant cut out as others have. We correlated BMD with local mechanical properties of trabecular bone to torque, and also with failure load of bone by side-impact as developed by Eckstein *et al.*¹⁵ We found that mechanical torque in the femoral head

measured by DensiProbe® in the proximal femur was weakly but significantly correlated with BMD and failure load of femoral bone. The weak correlation could be explained by the regional or local measurement in only one area of the femur. This might not be the weakest region of the bone and, therefore, fracture onset could be elsewhere. Correlation of implant anchorage in the middle of the femur head might represent the exacter for prediction of implant cut out, and this is a limitation of our analysis.

We could also demonstrate that gender differences in mechanical properties of bone (peak torque - DensiProbe®, load to failure) are higher than differences in BMD *in vitro* (Table 1).

In contrast to our study, Suhm *et al.* analyzed 16 fresh frozen femoral bones and correlated measurements of mechanical peak torque measured by DensiProbe® with BMD and anchorage of implants.¹⁰ Therefore, our correlation of mechanical peak torque (measured by DensiProbe®) with load to failure of femoral bone ($r=0.62$) could not be compared directly with their correlation of mechanical torque and implant cut out ($r=0.795$), whereas the correlation of peak torque and BMD could be compared in both analyses. Suhm *et al.* found a correlation

Table 1. Mean (\pm standard deviation) values and gender differences.

	Total (n=160)	Male (n=90)	Female (n=70)	Difference
K-wire indentation force (N)	99.5 (± 592.4)	1227.6 (± 609)	710.6 (± 426.6)	-42.1%*
Mechanical peak torque Densiprobe® (Nm)	3.48 (± 2.34)	4.41 (± 2.32)	2.26 (± 1.74)	-49%*
Failure load (N)	4050.2 (± 1586.7)	4866 (± 1447.6)	2991 (± 1045)	-39%*
T-value	-1.92 (± 1.46)	-1.44 (± 1.2)	-2.59 (± 1.47)	-45%*
Neck BMD (g/cm^2)	0.813 (± 0.201)	0.906 (± 0.16)	0.687 (± 0.177)	-24%*
Trochanter BMD (g/cm^2)	0.685 (± 0.188)	0.778 (± 0.15)	0.559 (± 0.156)	-28%*
Upper neck BMD (g/cm^2)	0.546 (± 0.16)	0.611 (± 0.14)	0.457 (± 0.14)	-25%*
Ward's triangle BMD (g/cm^2)	0.511 (± 0.17)	0.576 (± 0.151)	0.423 (± 0.15)	-26%*

BMD, bone marrow density recorded by DXA; T-value, number of standard deviation above or below the mean BMD for a healthy 25-year old adult of the same gender and ethnicity; * $P<0.001$ (\pm standard deviation).

Table 2. Correlation of mechanical peak torque, failure load and bone marrow density of different regions in the proximal femur *in vitro*.

r	Torque densi-probe® (Nm)	Failure load (N)	T-value	Neck BMD (g/cm^2)	Troch-anter BMD (g/cm^2)	Upper neck BMD (g/cm^2)	Ward's BMD (g/cm^2)
Indentation force K-wire (N)	0.883*	0.573*	0.616*	0.644*	0.650*	0.644*	0.633*
Densiprobe®							
Torque (Nm)		0.614*	0.602*	0.640*	0.636*	0.631*	0.623*
Failure load (N)			0.743*	0.790*	0.777*	0.798*	0.758*
T-value				0.985*	0.936*	0.883*	0.918*
Neck BMD (g/cm^2)					0.963*	0.895*	0.923*
Trochanter BMD (g/cm^2)						0.836*	0.854*
Upper neck BMD (g/cm^2)							0.940*

BMD, bone marrow density recorded by DXA; * $P<0.001$; r, correlation.

of $r=0.902$ with $P<0.001$ and we found weak correlation of $r=0.64$ with $P<0.001$. The influence of formalin fixation and embalming on mechanical properties of bone is controversial. Whether there was a systematic error as a result of the hardness from the long-term exposure to formalin during embalming in our study is not clear. We used formalin fixation of the bones in our study whereas Suhm *et al.*¹⁰ used fresh frozen bones. Öhman *et al.* showed that low concentrations of formalin in the short term have no effect on the mechanical properties of bone, but long-term preservation significantly affected Young's modulus, yield strain and ultimate strain of bone to compression.¹⁶ In contrast, even after only one year's embalming, van Haaren *et al.* found no significant differences when they compared formalin-fixed goat bone with fresh-frozen bone. There was only a slight tendency to increasing hardness of the formalin-fixed bone. But they found no difference in BMD.¹⁷ In 2010, Unger *et al.* compared three different embalming techniques after six months with fresh frozen bones, and could demonstrate that plastic energy absorption of the cortical bone is decreased by formalin fixation, thus the load to failure might be affected.¹⁸ Whether there is an effect on the trabecular bone and, therefore, an impact on the DensiProbe® measurements still remains unclear. Another biomechanical analysis of embalming was carried out by Edmondston *et al.* who found that there was no significant difference in failure strength, but the formalin-fixed group had a lower failure load, in contrast to the results of van Haaren and Unger *et al.*^{18,19}

Lochmüller *et al.* showed that formalin had no effect on DXA and BMD after ten months embalming in a solution of 5% formalin and 95% ethanol, the same embalming concentration as used in this present study.¹⁴ Nevertheless, the accuracy of DXA in removed samples and *in situ*

have been well-studied, and depend on the homogeneity of fat, the different depth of tissue, and the extra-skeletal calcifications.²⁰ In contrast to Suhm *et al.*,¹⁰ we used *in vitro* DXA and simulated soft tissue to minimize systematic errors.¹⁴ With no soft tissue, there is no difference in absorption between fat or muscle, and, therefore, DXA scans might overestimate the strength of bone.²¹

The exact correlations between mechanical torque, BMD and failure load of bone are not yet known. To our knowledge, this is the first time that obvious gender differences have been reported in this way. In our analysis male bones were approximately five years younger than female bones, reflecting the natural life expectancy of the human population. Because of the large number of bones in our study, separate correlations could be drawn for men and women. The significant differences between genders in failure load of bone, mechanical properties and BMD might be the result of gender-specific differences in the size, shape, and age of the bones.⁸ Women had 49% lower peak torque and 45% lower T-scores, whereas BMD (regardless of region) was only 24-29% lower in women compared with men. In 2010, Rodriguez-Soto *et al.* found significant correlation $R^2=0.72$ ($P<0.05$) when using logistical regression of torque measurement with the DensiProbe® device with BMD in 9 intertrochanteric fractures.²²

Measurements of torque and anchorage of screws, together with failure load of bone, are fields of high interest in orthopedic trauma surgery. The results of spine surgery, torque measurements of vertebra and the newly developed DensiProbe-Spine® are not comparable with the mechanical properties of the proximal femur.²³⁻²⁶ The architecture and size of the bones differ between vertebra and proximal femur, as do requirements of load bearing. The mechani-

cal properties of bone are more complex and can not be described by BMD or peak torque values alone.²⁷ In 1996, Augat *et al.* first discussed the geometric properties of the cortical shell that contribute to the strength of the skeleton.²⁸ Bone is not composed of uniform material, so various mechanical properties are needed to describe bone strength; trabecular architecture, cortical thickness, porosity, geometry and mineral content, all contribute to bone strength. In addition, these properties must be kept in mind while fixing an implant in the skeleton, including the bone-implant interface that varies according to the geometry (size and shape) of the implant, the surface design, and the material used.²⁹⁻³¹ Different load requirements demand axial loads, and forces of bending and torsion at the implant-bone interface, so regional geometrical requirements must be considered. Mechanical torque measurements mainly reflect the mechanical properties of the trabecular architecture, whereas anchorage of the implant and cut out describe the cortical and trabecular strength of bone and the implant-bone interface.¹⁰ Recording failure load using side-impact trials, therefore, sums up the bony mechanical properties of trabecular and cortical bone, and indicates the structural strength of whole bone. This can be described as maximum compressive strength.¹⁵ In 2008, Böhm *et al.* studied quantitative gray-level topology using the Minkowski functional (MF), compared it with BMD, and found it to be superior in the prediction of maximum compressive strength of bone to predict the risk of fracture.³² In orthopedic trauma departments, pre-operative DXA or QCT are rarely available, so other ways are needed to estimate bone strength and anchorage of implants in the perioperative period. Future analysis will aim to define a cut-off value at which implant-anchorage is too poor for standard osteosynthesis, to justify additional

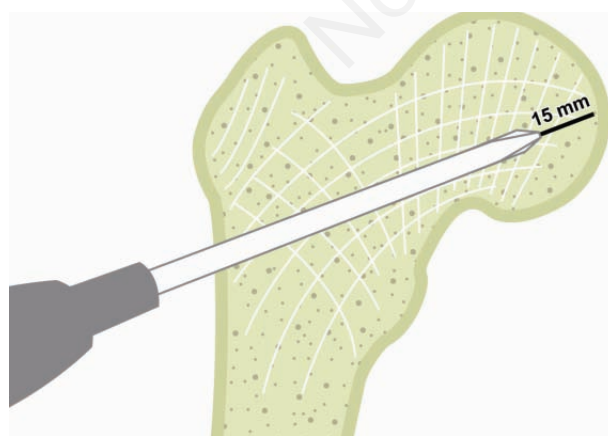


Figure 3. Schematic drawing of torque measurement with the DensiProbe® device. The DensiProbe® instrument is placed in the femoral neck. A schematic drawing of the proximal femur with inserted DensiProbe® device to measure torque breakaway of the trabecular bone 15 mm beneath the surface.

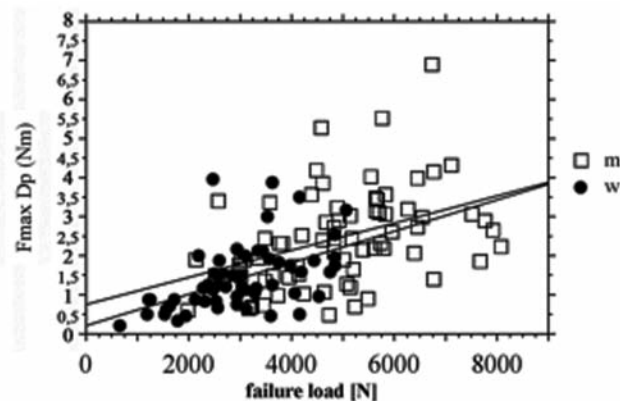


Figure 4. Bivariate scattergram with linear regression analysis. Correlation of failure load and mechanical torque (Fmax Dp). Fmax Dp, torque in [Nm] measured by Densiprobe®. Failure load in N, measured by side-impact. □ = male; ● = female.

cement augmentation or even a joint replacement by arthroplasty. In this way, we might be able to avoid implant cut out and the need for a second operation.

Conclusions

We demonstrate a correlation between mechanical peak torque of breaking away trabecular bone, the failure load of the proximal femur and BMD *in vivo*. Mechanical peak torque measured by DensiProbe® correlates with the T-score ($r=0.602$) and with BMD in the femoral neck $r=0.64$ ($P<0.001$), whereas failure load correlates better with the BMD (QCT) of different regions in the proximal femur (from $r=0.79$ femoral neck up to $r=0.798$ upper femoral neck). Moreover, good correlation was found between T-score and failure load of bone ($r=0.743$; $P<0.001$).

Measurement of mechanical torque by DensiProbe® may be useful for decision making, if pre-operative DXA or QCT are neither available nor possible.

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