Assessment of Femoral Neck Strength by 3-Dimensional X-ray Absorptiometry

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Abstract

Hip fractures due to osteoporosis are accompanied with increased mortality and morbidity. Bone mineral density (BMD [g/cm2]) measured by dual-energy X-ray absorptiometry (DXA) is the most important risk factor. However, an overlap exists between results of fractured and nonfractured populations. Macro-architectural parameters of the femur are independent risk factors of fracture. They have been evaluated in two dimensions using X-ray films or DXA scans; therefore, they are highly dependent on patient positioning and interindividual anatomical variations. To overcome this problem, we have previously shown the possibility to reconstruct human femurs using two perpendicular DXA scans and to calculate 3-dimensional (3D) geometric parameters from these reconstructions by a method called 3-dimensional X-ray absorptiometry (3D-XA). The aim of this article is to assess whether the combination of areal BMD and 3D geometric parameters calculated from 3D-XA improves failure load prediction of human proximal femurs in stance phase configuration. Twelve femurs (11 women, 1 man; aged 88–9 yr; range: 72–103 yr) were included in this study. The BMD was measured using a Hologic Delphi-W device (Hologic, Waltham, MA) and 3D reconstruction of the femurs was done using two perpendicular DXA scans as previously published. The calculated 3D geometric parameters included femoral neck axis length (FNAL), mid-femoral neck cross-sectional area (mid-FN CSA), neck shaft angle (NSA), and femoral head diameter (FHD). Mechanical testing was performed using stance phase configuration, which resulted in subcapital fractures. The FHD was correlated to mid-FN CSA and FNAL (r = 0.68 and 0.76, respectively; p < 0.001). Failure load was correlated to age, FHD, NSA, and BMD measurements. Multiple regression analysis showed that femoral neck BMD, FHD, and mid-FN CSA gave the best statistical model for failure load prediction (r² = 0.84; p < 0.002). This is the first study suggesting that combining areal BMD to 3D geometric parameters obtained by 3D-XA improve failure load prediction in human femurs.

Key Words: 3D-XA; bone densitometry; DXA; failure strength; geometry.

Introduction

Hip fractures represent the most serious consequences of osteoporosis (1,2). Increased morbidity and mortality are related to hip fracture (3,4).

Bone mineral density (BMD [g/cm²]) measurement by dual-energy X-ray absorptiometry (DXA) is known to be the gold standard for bone mass measurement. Besides BMD, proximal femur strength depends on its 3-dimensional (3D) shape, the distribution of bone material within the entire structure, the micro-architectural properties of the distributed bone material, and the load conditions. Structural geometric parameters, such as hip axis length (HAL), femoral neck diameter, cross-sectional moment of inertia, or cortical wall thickness measured or calculated from two-dimensional (2D) data are correlated with hip strength (5,6) and hip

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fracture risk (7,8), but they are not evaluated in a routine clinical examination. Several biomechanical studies pointed out the potential for combining BMD measurements and macro-architectural measurements to explain failure load variability. However, macro-architecture measured on 2D images are sensitive to patient positioning and inter-individual anatomical variability, and accurate 3D geometric parameters obtained from the acquisition of quantitative computed tomography (QCT) require a definite increase of radiation dose compared with DXA scans.

Recent advances in the stereoradiographic reconstruction technique (9) allow obtaining 3D bone geometry from 2D contours identified on bi-planar radiographs. This 3D stereoradiographic reconstruction method was already applied on the proximal femur (10) with accuracy close to the one obtained by 3D computed tomographic (CT) scan reconstruction. The possibility of using DXA scans obtained on standard DXA devices to obtain similar results was shown in a previous study (11).

The aim of the current study is to use this 3D reconstruction method and to combine 3D geometric structural parameters with DXA BMD measurements to estimate the fracture load prediction of human proximal femurs mechanically tested in stance configuration.

Materials and Methods

Fourteen human femurs were collected according to the Ethics Committee Agreement of St Pére Anatomy Institute (Paris, France). However, results were unusable for two specimens due to technical problems on sensors during mechanical testing. Finally, the study comprised 12 femurs from 11 females and 1 male (aged: 87.7 ± 9.3 yr [mean aged range: 72–103 yr]) within 10 days of death, cleaned of soft tissue, sealed in a plastic bag, and frozen at −20°C. Frozen specimens were trimmed with a handsaw approximately 10 cm below the lesser trochanter and the distal extremity was embedded in methyl methacrylate.

3D-XA Acquisitions

The DXA scans were performed with a Hologic Delphi-W (Hologic Inc., Waltham, MA). Because the DXA unit that was used had no C-arm for lateral acquisition, the anteroposterior (AP) and lateral acquisitions were successively achieved using a specific device allowing a 90° rotation around an axis parallel to the scanning direction. Each proximal femur was fixed to this device by the shaft with the femoral-neck axis parallel to the table. Thus, a linear scanning of each specimen was performed in two orthogonal positions (AP and lateral views). Soft tissues were simulated by immersing specimens in a 14-cm depth bath of water.

Densitometry

Bone densitometry analysis was performed on the AP view. Standard hip analyses procedures were used to measure bone mineral density (g/cm²) in different regions (i.e., the femoral neck, greater trochanter, and total hip BMD).

3D Geometry

The 3D stereoradiographic reconstructions of the 12 specimens were obtained using the nonstereo corresponding contour algorithm applied to the proximal femur (10). The details of this reconstruction algorithm have already been presented (9). In summary, the main steps are spatial calibration of the DXA device, successive frontal and lateral DXA acquisitions, identification of specific contours on both views, and deformation of the 3D generic object until its 3D projected contours match with the 2D identified ones. This 3D reconstruction technique applied to the DXA device provides a reproducible 3D personalized model with an accuracy close to CT scan with an absolute mean difference of 0.8 mm (2 root mean square = 2.1 mm) (11). Once the 3D personalized model is obtained, several structural parameters were automatically calculated (Fig. 1): femoral neck axis length (FNAL), mid-femoral neck cross-sectional area (mid-FN CSA), neck-shaft angle (NSA), and femoral head diameter (FHD) as previously

![Fig. 1. Illustration of geometric parameters calculated from 3-dimensional (3D) personalized models: (γ, neck-shaft angle; d₁, femoral neck axis length; d₂, femoral head diameter).](image-url)
The reproducibility of these parameters calculated from 3D-XA was 1.4% for FHD, 5% for mid-FN CSA, 0.7% for NSA, and 1.1% for FNAL (11).

Mechanical Testing

The stance phase mechanical testing was selected because previous studies showed that it sheared the femoral head from the femoral neck in a manner consistent with clinical subcapital fractures (12,13). Thawed specimens were fixed by the femoral shaft (fit into low temperature melting alloy) at an angle from 25° to the vertical (Fig. 2). A customized femoral head cup was produced in methyl methacrylate for each specimen. A vertical displacement rate of 12.7 mm/min was initiated; the vertical displacement and the compression strength applied were measured during the test with sensors integrated in the mechanical compression device. Fractures were classified using the Association for Osteosynthesis (AO) fracture classification of long bones (14).

Statistical Methods

All data are presented as mean values ± standard deviation. First, correlation matrix was calculated for 3D geometric parameters. Second, Pearson’s correlation coefficient (r) was used to describe the association of each parameter with force failure. To evaluate the capacity of a statistical model associating densitometric and 3D geometric variables to predict fracture load, ascending multiple linear regression analyses were performed. For each of these analyses, determination coefficient (R²), adjusted determination coefficient (adjusted R²), and the significant contribution of each variable to the model (p value of t test) were given. It has to be mentioned that adjusted R² allows the introduction of a correction of the R² in step with the number of variables used and their significant contribution to the model. Results were considered statistically significant at a p value ≥ 0.05.

Results

All produced fractures were located in the cervical area and of subcapital pattern (type B1 and B3 of AO classification). This demonstrated the capacity of the mechanical setting to produce reproducible subcapital fractures. An example of fracture is shown Fig. 3. The mean fracture load was 5668 ± 1597 Newtons. Table 1 shows load failure measurements for the whole sample.

Calculated 3D geometric parameters are also given in Table 1 with mean values of 88.9 ± 3.5 mm for the FNAL, 634 ± 88 mm² for the mid-FN CSA, 119.9 ± 3.8° for the NSA, and 42.6 ± 1.9 mm for the FHD.

Densitometric measurement for greater trochanter area, femoral neck area, and total area are presented in Table 1 as well.

![Fig. 2. Geometrical positioning of the specimens to establish stance configuration.](image1)

![Fig. 3. Example of typical subcapital fracture obtained from mechanical testing.](image2)
The FHD was correlated with mid-FN CSA and FNAL ($r = 0.68$ and $0.76$, respectively; $p < 0.001$). Other correlations were not significant.

Pearson’s tests applied between failure load and explicative variables yield significant linear relation for age, NSA, FHD, and BMD measurements (Table 2). Multiple linear regression taking into account BMD at the femoral neck, FHD, and mid-FN CSA gave the best statistical model for failure load prediction ($R^2 = 0.84$; adjusted $R^2 = 0.78$; $p < 0.002$) with all these parameters significantly contributing to the regression model ($p < 0.05$). Failure load prediction by the femoral neck BMD alone was $r^2 = 0.50$ ($p = 0.02$). Adding FHD improved prediction ($r^2 = 0.68$; $p = 0.03$). Failure load prediction was further improved by adding mid-FN CSA to the model ($r^2 = 0.84$; $p = 0.001$): (failure load $= 8116.8$ neck BMD $- 673.1$ FHD $+ 10.4$ mid-FN CSA $+ 23912.5$). The other parameters were rejected from the model.

### Discussion

Limitations of in vitro studies to assess fracture risk are well known. Not only the bone failure load associated to its

![Graphical representation of the multiple linear regression model.](image-url)
BMD and geometry has to be taken into account, but also the weight of the subject and his musculature. Big people have larger and stronger bones, but also fall with larger forces. Nevertheless, bone failure load estimation is one of the key factors. This study is the first to combine 3D parameters from DXA acquisition with BMD to evaluate failure load prediction. Previous studies using DXA have used 2D parameters as HAL, FNAL, FHD, and NSA to improve fracture risk estimation. However, these parameters are sensitive to patient positioning and inter-individual anatomical variations (15,16). Some geometric parameters as mid-FN CSA are not available on 2D examination, but have been estimated using some geometrical assumption concerning the femoral neck shape. These limitations led investigators to develop a 3D method from CT scan acquisition (17,18). The 3D-XA method does not have the drawbacks of high radiation dose generated by CT scanning and provides both reproducible and accurate 3D geometric parameters (11). The mean difference between the 3D-XA and 3D CT reconstruction of in vitro proximal femurs ranged from 0.6 to 1.2 mm according to the region. Higher errors were situated at regions as the lesser trochanter (i.e., of limited importance in bone strength).

As in previous studies, using a similar biomechanical configuration (13,19–21), all produced fractures were in the cervical region. Our study correlation test performed between fracture load and femoral neck BMD showed a significant determination coefficient \( R^2 = 0.50; p = 0.02 \), which is in the lower range of previous published data from studies using both an approximately similar biomechanical configuration and DXA devices for BMD measurements (0.42 < \( R^2 < 0.72 \) (6,21–23). For BMD measured on total hip and greater trochanter, determination coefficients were also lower in our study than in these studies. Lower determination coefficients found in our study could be partly explained by the tighter distribution of age compared with populations of previously cited studies, and it is well known that determination coefficients are improved when there is a wide distribution of the values.

Concerning 3D geometric parameters, FHD and NSA were significantly correlated with failure load \( R^2 = 0.41 \) and \( R^2 = 0.30 \), respectively; \( p < 0.05 \). The first result is in accordance with two previous biomechanical studies using stance phase configuration measuring FHD in 2D (6,24). The same studies have not found any significant correlation between NSA and failure load. However, one of the studies (6) found a significant correlation between FNAL and failure load. Our study tested only one type of intracapsular hip fracture (i.e., the subcapital). Our results can not be applied to other types of fractures. Different regression models would predict different types of hip fractures. We also tested the stance configuration model. Subcapital fractures resulting from fall can not be predicted with the same regression model.

Our results suggest that adding 3D geometric parameters by 3D-XA method to classical BMD measurements improves failure load prediction of human femurs. Our study was conducted on a comparable number of specimens and used a comparable mechanical testing technique (position of the specimens, displacement rate) to that of Lang et al. (20). In their study they measured volumetric BMD of the whole femoral neck by QCT as well as 3D parameters (FNAL, min-FN CSA). Their multiple regression analysis yielded a regression model with the same significant contributing parameters (FNAL being correlated to FHD, both partly reflecting the bone size). This approach, combining 3D geometric parameters and BMD measurements, induced an improvement of 34% of the failure load variability explanation \( (R^2 = 0.59 \) to 0.93), which is very similar to our results \( (R^2 = 0.50 \)–0.84).

The main limitation of our study is the small sample size, and its conclusions can not be generalized. Further studies are needed to confirm our results. The small sample size is a major limitation to compare the 3D-derived geometric parameters to 2D-derived ones. Another limitation is the use of stance phase configuration model; the results could be different if we had used the lateral fall configuration giving different types of hip fracture. Nevertheless, the 3D-XA method could be applied in vivo, especially with the DXA devices equipped with a C-arm. As lateral view is not optimal for hip examination, due to superposition of the contralateral femur and the pelvic bones, allowing the C-arm to stop at different angles could be necessary. Further in vivo studies with fractured and nonfractured patients are needed to confirm our in vitro results.

In conclusion, this study is the first biomechanical study associating 3D geometric parameters derived from 3D-XA and classical BMD measurements. It suggests that this combination could improve failure load prediction.

References


