Finite element analysis of DXA images (FEXI) for the prediction of osteoporotic fractures

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Osteoporosis and prediction of fracture risk

Osteoporosis describes a period of largely asymptomatic bone loss with an associated skeletal fragility and increased risk of fracture. In the UK alone, the number of subjects suffering a fracture of the distal radius and proximal femur exceeds 60,000 and 50,000 per annum respectively, with an estimated cost above £1 billion. As a quarter of hip fracture subjects die within 12 months, while a quarter of those remaining never regain independent status, there is therefore an increasing need to identify subjects at risk of osteoporotic fracture in order to provide preventative clinical management.

Currently, the preferred method of assessing the risk of an osteoporosis related fracture is a measure of bone mineral density (BMD) by dual energy x-ray absorptiometry (DXA) where BMD is utilised as a surrogate for mechanical integrity, explaining between 70% and 85% of the variance. It is generally accepted that for fracture risk assessment of a particular bone, BMD measurement should be performed at that anatomical site, for example, BMD at the forearm provides the best prediction for distal radius fracture.[1] We know, however, that other factors contribute to the overall risk of fracture, including anatomical geometry and the spatial distribution of bone.[2,3] Although spatial information is currently recorded in the form of a DXA image, this information is not utilised clinically. It should be noted that BMD assessment provides an areal density measure, where the cross-sectional scan area is known but not the tissue thickness, providing units of $g\ cm^{-2}$.

Finite element analysis

Finite element analysis (FEA) is a widely-used technique for the computer modelling of structures under mechanical loading. A finite element is an individual regular shape that has a known stiffness so that any applied load will give a predictable corresponding displacement. Elements are joined together at nodes and along edges. Complex designs are created as an assembly of elements to which restraints and loads may be applied. During the computer analysis of the model, a series of simultaneous equations are established that represent the overall stiffness of the structure. The equations are then solved giving the nodal displacements resulting from the applied loads. For the analysis of bone structures, finite element analysis would therefore be dependent upon the density of each element, the arrangement of elements (eg trabecular structure), the composition (eg cortical shell or cancellous) and the external shape (eg length, angle and width of femoral neck).

FEA has previously been applied to computer modelling of several bioengineering situations incorporating bone including cellular remodelling, prosthetic loosening, fracture progression and fracture healing. Studies related to osteoporosis have tended to utilise the full 3D potential of FEA via incorporation of computed tomography (CT) data. For example, Cody et al[4] demonstrated that 3D FEA explained 20% more of the variance in femoral strength than conventional DXA-derived BMD data. Keyak et al[5] reported significant correlation between measured and finite element predicted femoral fracture load. They concluded, however, that "clinical use of this approach, which would require additional x-ray exposure and expenditure for a CT scan, is not justified." Although being technically more advanced than DXA, CT is not routinely utilised in clinical assessment of fracture risk, being more expensive and administering a higher radiation dose.

FEA predicts the mechanical behaviour (displacement or stress) of a structure under loading rather than the exact yield point (fracture); but since osteoporosis fracture risk assessment requires only a proportional, rather than exact, measure of fracture load, FEA derived stiffness (load / displacement) should have significant clinical potential. In Hull, we are working on the technical development and clinical

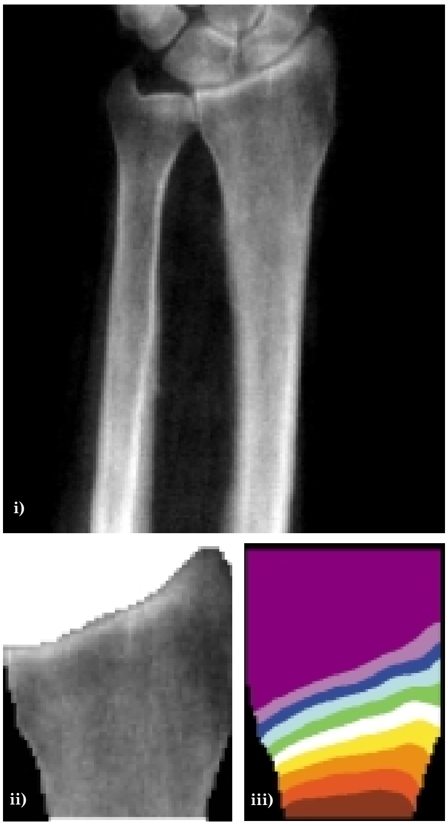

FIGURE 1
Image processing stages associated with FEXI. Illustrated for analysis of the distal radius: i) original DXA image of the forearm; ii) removal of external soft tissues/bones and application of the loading platen to conform to the curved surface of the distal face, and iii) displacement plot from finite element analysis.

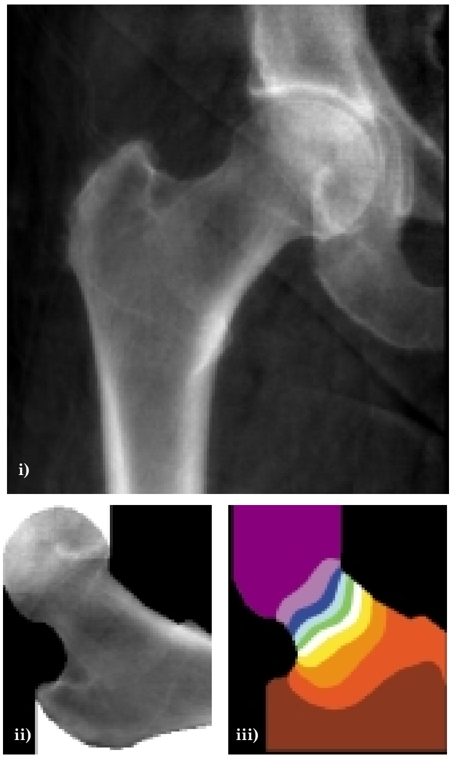

FIGURE 2
Illustrated for analysis of the proximal femur (as figure 1).

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evaluation of a novel 2D FEA-based technique utilising conventional DXA-derived spatial images that will hopefully provide a quantitative and accurate measure of a subject's fracture risk. FEXI (finite element analysis of x-ray images) provides a 'thin plate' computer simulation of a bone being mechanically tested.

FEXI methodology

1, A conventional DXA image is first exported and converted into 8-bit bitmap (BMP) format, providing 256 levels of grey scale. The grey level of each individual pixel within the digitised BMD image therefore corresponds to the apparent areal density within that pixel.

2, The image is manually modified via a desktop art-package to delete pixels beyond the extent of the bone of interest (eg distal radius or proximal femur), namely soft tissue and other bones. It should be noted, however, that the 'bone' image could include artefacts of overlying soft-tissues and other bones (eg distal tip of ulna or pelvis).

3, A FEA script file is created from the bone bitmap image via a bespoke computer program. The Young's modulus of each image pixel is derived from the pixel's grey level via a three-stage process:

- between BMD and image grey level was derived via DXA scanning of a seven-level aluminium step wedge.
- BMD is converted into volumetric density by arbitrarily considering the bone to have a constant depth.
- density of each pixel is converted into Young's modulus from published regression data.

4, FEA simulation of a mechanical compression test is achieved by placing the bone image between a support base and loading platen. The bottom horizontal edge of the bone image is restrained in both vertical and horizontal directions. To facilitate even load distribution, the lower surface of the loading platen is shaped to conform with the curved upper surface of the bone image.

5, By dividing the known applied load by the recorded vertical displacement of the platen, the mechanical stiffness (N mm^{-1}) may be derived.

Clinical pilot studies

Two clinical fracture discrimination pilot studies have been performed to date. The first considered the ability of FEXI to discriminate subjects who had, or had not, suffered a distal radius fracture, utilising forearm DXA images. The second considered miscellaneous osteoporotic fractures utilising hip DXA images. For both studies, DXA images were derived from the Lunar Expert fan-beam scanner.

For the 'distal radius' study, the contra-lateral forearm of 10 subjects who had previously suffered a distal radius fracture were compared with 10 control subjects, being matched for BMI and handedness, the fracture group being slightly older ($p=0.008$) and shorter ($p=0.06$).

For the 'proximal femur' study, 10 subjects with an osteoporotic fracture were compared with 10 age and BMI matched control subjects.

FEXI data for fracture and control populations was compared with BMD results for various conventional anatomical sites, the results shown in the table below as p values (Independent Sample Test) and Receiver Operator Characteristic areas (mean, 95th percentiles).

These early results suggest that FEXI provides superior fracture discrimination to conventional DXA, the current 'gold standard'. In order to further validate the FEXI technique, two studies have recently been initiated. The first is a clinical retrospective fracture discrimination study of subjects who have, or have not, suffered a recent hip fracture, utilising proximal femur DXA images. The second is an in-vitro scientific validation study, comparing the performance of FEXI and conventional BMD to predict the stiffness and yield load of mechanically tested porcine femurs. For this latter study, the relative performance of FEXI utilising plain radiographs and DXA images will be compared. It is interesting to note that the spatial resolution for these imaging modalities is approximately 50µm and 800µm respectively, with plain radiographs offering additional 'textural' detail.

Summary

Finite element analysis inherently offers dependence upon the external shape and internal structure of a bone and should, therefore, have the potential to provide a superior prediction of mechanical integrity than simple areal density (BMD). The novel feature of the FEXI approach is that a conventional mechanical compression test is simulated. An important aspect of the technique is that, being based upon conventional 2D DXA images or radiographs, it could be readily utilised into routine clinical practice.

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