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Investigation of Repeatability in Hip Fracture Risk Predicted by DXA-based Finite Element Model *

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Abstract—**DXA (dual energy X-ray absorptiometry) based finite element model is able to integrate all mechanical factors affecting hip fracture in osteoporosis patients and it is thus, in principle, more reliable than areal bone mineral density (BMD) for assessing fracture risk. However, short-term repeatability of DXA-based finite element model in predicting fracture risk has not yet been investigated and satisfactory repeatability is a prerequisite for the procedure to be applied in clinic. Therefore, in the reported research, the repeatability of a previously developed DXA-based patient-specific finite element procedure was investigated. It was found that inconsistence in positioning the patient during DXA scanning and manual segmentation of DXA image in constructing the finite element model are the two dominant factors affecting short-term repeatability of the finite element procedure. The study outcome indicated that to apply the finite element procedure in clinic, a set of more strict guidelines for positioning the patient in DXA scanning must be established and followed.**

I. Introduction

Hip fracture due to osteoporosis has been identified as a major health concern for the elderly [1-5] and it is also a heavy burden for the healthcare systems in North America [6-9]. With effective treatment options now available for osteoporosis patients, accurate assessment of fracture risk has become a critical step in the treatment process, both for the purpose of initial screening and for monitoring the effectiveness of a treatment. Measurement of areal bone mineral density (BMD) at the femoral neck using hip DXA image is currently the reference standard designated by the World Health Organization (WHO) for the diagnosis of osteoporosis [10], which is currently also used as a surrogate for predicting fracture risk. However, studies have revealed that areal BMD alone is not effective for assessing fracture risk, as the majority of osteoporotic fractures occur with T-scores above the "osteoporotic" threshold [11, 12]. On the other hand, Asian women have lower bone mass than white women, but interestingly the rate of hip fractures is not proportionally higher, it is instead 40-50% lower than white women [13]. The reason is that some of the important parameters contributing to bone fracture are not considered in the current DXA assessment procedure. Based on Mechanics of Materials, bone fracture is governed by three categories of parameters: bone mechanical properties, bone geometry and body weight. Areal BMD partially reflects mechanical properties of bones, but the other two categories of parameters are missing from the current clinical procedure for assessing fracture risk. DXA-based finite element model [14-19] is able to incorporate not only BMD but also femur geometry and body weight based on well-established mechanical theories. A DXA-based finite element modeling procedure was proposed by Luo et al. [14] for improving prediction of hip fracture risk. There are a number of unique features with the proposed procedure. The finite element model is patient-specific, i.e., the patient's areal BMD, femoral (projected) geometry and body weight are considered in the model. However, short-term repeatability of the procedure has not been studied yet and this must be done before it can be applied to in clinic, as only a highly repeatable procedure can provide reliable information for the assessment of hip fracture risk. Our objectives were to identify the dominant factors affecting short-term repeatability of the procedure and thus to improve the reliability of the procedure in clinical application.

II. Methods and Materials

A. DXA-based patient-specific finite element model and fracture risk index

The DXA-based patient-specific finite element procedure proposed in [14] for assessing hip fracture risk is illustrated in Figure 1 and briefly described in the following for completeness.

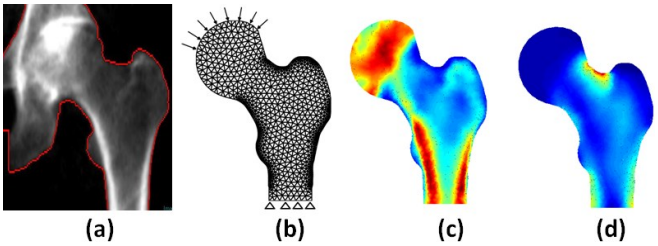

Figure 1. DXA-based finite element procedure

The procedure starts with hip DXA image of the concerned patient. The contour of the proximal femur is segmented from the DXA image and used to generate a finite element mesh. An impact force that is induced in lateral (sideways) fall and is proportional to the patient's body weight is applied in the finite element model. Bone elasticity modulus and yield stress are correlated to areal BMD using empirical relations [14, 17, 20]. Stress distributions in the proximal

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femur are obtained by finite element analysis and fracture risk indices are calculated from the obtained stresses.

To measure fracture risk at the femoral neck, the following fracture risk index (η) was introduced,

$$\eta = \frac{\sum_{i=1}^{N} \int_{A_i} \frac{\sigma_{\text{eff}}}{\sigma_Y} dA}{\sum_{i=1}^{N} A_i} \quad (1)$$

Where A_i (i = 1, 2, … N) are the areas of the N finite elements enclosed in the region of interest as shown in Figure 2. σ_{eff} and σ_Y are, respectively, the effective stress (or von Mises stress) induced by the impact force and the yield stress of the bone.

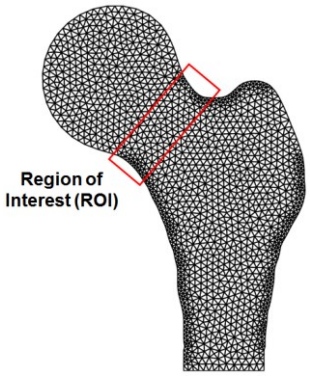


Figure 2. Regions of interest for assessing fracture risk

All DXA images used in this study were obtained from the population-based Manitoba Bone Mineral Density Database (MBMDD) [21] after anonymization to electronically remove all personal information as required under the human research ethics approval. All DXA images were scanned using Lunar Prodigy DXA machines (GE HealthCare) with a standard scan mode (37.0 μGy). In total, 30 typical clinical subjects were randomly selected from the quality assurance database established for measuring test repeatability. Each case had initial imaging and then repeat imaging within a few days so that the BMD would not be expected to change. Most scans were done on different days by different technologists, a "worst" scenario in terms of measurement error but most accurately reflects routine clinical practice. All subjects in the selected cases were white females. The average age of the subjects was 60 years, with a range from 26 to 80. Each DXA image was converted to a MATLAB mat-file by in-house developed MATLAB codes, which outputs a pixel-by-pixel areal BMD map that can be read into MATLAB. The output mat-file with areal BMD distribution was used in constructing the patient-specific finite element model [14].

B. Factors affecting repeatability of fracture risk index

In theory, for each case, the two finite element models constructed respectively from the initial and the repeat DXA image should generate the same fracture risk index, as there is no expected change in the subject's body weight, bone geometry or bone mineral density in the short period separating the two scans. In reality, fracture risk indices generated by the two finite element models are not identical due to uncontrollable factors (i.e., measurement error) involved in the DXA scanning process and in the construction of the finite element model.

To investigate repeatability of the DXA-based finite element procedure [14], a number of factors were identified, which include finite element mesh density, Gauss integration order used in calculating element stiffness matrix, manual segmentation of DXA image and patient positioning in DXA scan. The effects of the factors were investigated using the following designed steps:

1) The same segmented DXA image was used to construct two finite element models to investigate effects of finite element mesh density and Gauss integration order.
2) The same DXA image was segmented twice to study effect of manual segmentation.
3) The pairs of initial and repeat DXA scans were used to investigate effect of patient positioning.

To measure repeatability of the DXA-based finite element procedure, the following coefficient of variation (CV) was adopted, which is proposed in Gluer's study [22],

$$CV = \sqrt{\frac{\sum_{j=1}^{m} CV_j^2}{m}} \quad (2a)$$

$$CV_j = \frac{SD_j}{\overline{\eta}_j} \quad (2b)$$

$$\overline{\eta}_j = \frac{\eta_j^{(1)} + \eta_j^{(2)}}{2} \quad (2c)$$

$$SD_j = \sqrt{\frac{1}{2}\left[(\eta_j^{(1)} - \overline{\eta}_j)^2 + (\eta_j^{(2)} - \overline{\eta}_j)^2\right]} \quad (2d)$$

In the above equations, m is the number of cases studied; $\eta_j^{(1)}$ and $\eta_j^{(2)}$ are fracture risk indices predicted by paired finite element analyses; $\overline{\eta}_j$ is the average of them. SD_j is the standard deviation of case j.

III. Results and Discussions

In the first step, the same segmented DXA contour was used to construct two finite element models, and the same mesh density, the same Gauss integration order and the same loading/boundary conditions were used in the two finite element models, it was found that there is no difference between the predicted fracture indices. The above result indicated that the finite element procedure starting from a segmented DXA is completely repeatable. Then, the same DXA image was segmented twice, and the two DXA contours were used to construct two finite element models, coefficient of variation (CV) in the predicted fracture risk index was calculated as 1.39% for the 60 DXA images in the 30 cases. In the third step, the paired initial and repeat DXA scan were used to construct two finite element models, coefficient of variation in the predicted fracture risk indices was obtained as 6.42% for the 30 cases. It should be noted that in all the paired finite element analyses, the other conditions such as finite element mesh density, Gauss

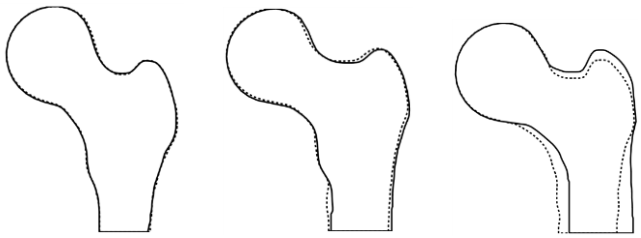
integration order, loadings and constraints were kept the same, so that they would not introduce variations into the paired fracture risk indices predicted from the finite element models. Material properties are also the same in the paired finite element models in the 1) and 2) step analyses. However, they may be different in the 3) step finite element models due to noise and inconsistent positioning of patient.

For clinical application, coefficient of variation in a measurement is generally required below 2% [22]. Therefore, the overall repeatability (6.42%) in fracture risk indices predicted from the patient's initial and repeat DXA scan does not satisfy the requirement. To investigate the possible causes, overlap between the two femur contours segmented from the patient's initial and repeat DXA scan was studied. To measure difference between the two contours, a quality index (q) was defined as

$$q = \frac{2\overline{A}}{A_1 + A_2} \qquad (3)$$

In the above definition, A_1 and A_2 are respectively the areas of the two contours; $\overline{A}$ is the overlapped area of the contours. The quality index is a composite measure of inconsistency and error induced in scan positioning and in manual segmentation of the DXA image. A unit value of the quality index would represent an ideal quality and indicates a complete overlap of the two contours.

The 30 cases consisting of pairs of initial and repeat scans were classified into three categories using the quality index defined in Equation (3), i.e., poor ($q < 0.90$), moderate ($0.90 \le q \le 0.95$) and high ($q > 0.95$). Representatives from the three categories are shown in Figure 3. Based on the above criterion, the percentages of the three categories in the selected cohorts are, respectively, 30% high, 43.3% moderate and 26.7% poor quality.



(a) High (b) Moderate (c) Poor

Figure 3. Samples of different contour quality (solid and dashed lines representing contours segmented from the initial and repeat DXA image, respectively)

The cases having poor quality were removed, and then the coefficient of variation in the rest cases was re-calculated as 1.58%. Therefore, improvement in repeatability of femur contours is the key to improve repeatability of fracture risk indices, while the repeatability of femur contours is obviously determined by consistency of patient positioning in DXA scanning. Consistent positioning requires following more strict guidelines, for example, positioning the hip relative to a reference line so all patients would have the same length of scanned proximal femur, encouraging the patient to keep legs straight and with an optimal degree of hip internal rotation. One possible solution for improving DXA scanning is to use the quality index defined in Equation (3) during the repeat scanning to monitor the repeatability of the projected femur contour. Once a repeat DXA scan is acquired, the projected femur contour is immediately obtained and compared with that from the initial scan by an automatic computer program. If the quality index is lower than expected, DXA is re-scanned. The above process can be repeated until a satisfactory femur contour quality is achieved. Apparently the DXA-based finite element model used in this study can be further improved, for example, the linear elastic material model can be replaced by a more advanced model. However, it can be seen from this study, advances in the finite element model should not affect the repeatability of the finite element procedure as the involved factors are deterministic and would not introduce random error.

IV. Conclusions

The DXA-based finite element analysis process starting from a segmented femur contour is completely repeatable, i.e., no random error is introduced in this step. The errors induced by insufficient mesh density or integration order are algorithm errors and they indeed affect the accuracy of the predicted fracture risk indices. However, algorithm errors are deterministic and, therefore, do not affect the repeatability of the DXA-based finite element procedure. Only random errors affect the repeatability of the procedure and make differences in the predicted fracture risk indices. Random errors in the DXA-based finite element procedure were mainly introduced by inconsistent positioning in DXA scanning, followed by manual segmentation of the projected femur contour. Refining finite element mesh and increasing Gauss integration order are useful to reduce algorithm errors, but they are not helpful in reducing random errors. Therefore, they were not able to improve repeatability of the predicted fracture risk indices. Random errors induced by inconsistent subject positioning may be partially eliminated by applying image processing techniques such as image translation and rotation, but these errors cannot be completely removed. To apply the DXA-based patient-specific finite element procedure in routine clinical assessment of hip fracture risk, a set of more strict guidelines should be adopted to reduce inconsistency of subject positioning in DXA scanning, and the femur contour should be segmented from DXA image automatically by a well-designed algorithm.

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