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ASSESSMENT OF HIP FRACTURE RISK WITH AN IMAGE-BASED THREE-LEVEL BIOMECHANCIAL MODEL

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ABSTRACT

Accurate assessment of hip fracture risk is necessary for taking appropriate preventive and protective measurements. Conventional population-based statistical models are not accurate in predicting fracture risk in individual subjects. Single-level biomechanical models are not able to accommodate all biomechanical variables that take effects at different musculoskeletal levels. We developed an image-based three-level biomechanical model to predict hip fracture risk caused by sideways fall from standing height. A small-scale clinical study was conducted to examine the ability of the three-level model to discriminate clinical hip fracture cases from matched controls. The obtained results show that the model has superior performance than the existing clinical tools.

INTRODUCTION

Fall-induced hip fracture is a major cause of suffering, disability and death for elderly people around the world [1]. Over 30,000 hip fractures occur each year in Canada [2]. By the year 2041, the number of hip fractures in Canada is expected to quadruple [3]. The annual cost of hip fractures in Canada was estimated at $650 million in 1993 and is expected to increase to $2.4 billion by 2041 [3]. The risk of hip fracture is determined by two factors [4]: the strength of the affected femur and the impact force induced by an accidental fall; if the impact force exceeds the strength of the femur, hip fracture will occur. The high incidence of hip fractures among elderly people is due to the prevalence of osteoporosis among this group and their propensity for accidental fall. Osteoporosis is an age-related skeletal disorder that can substantially reduce the strength of bones. In Canada, the prevalence of osteoporosis is reported to be 26% in women and 7% in men over age 50 [5]. According to a report released by the US National Osteoporosis Foundation (NOF) in 2014 [6], about 54 million Americans are affected by osteoporosis and low bone mass. Along with age-related degeneration in neuromusculoskeletal functions, elderly people become more and more prone to falling [7]. The impact force induced in a fall, even in a low-trauma fall from standing height, usually has a large magnitude that can be ten-fold or more of the normal physiological loading [8]. Although the force would not cause any serious harm to a healthy subject, it is a great risk for osteoporosis patients [9, 10].

Osteoporosis is a 'silent disease' as it has no symptom until the patient's first-time fracture. It is desirable that high-risk patients can be timely and accurately identified so that they can benefit from effective treatments. To assess osteoporotic fracture risk in elderly people, a large number of tools have been developed from either population-based statistical models [11, 12] or biomechanical models [13, 14]. The population-based tools were developed from statistical associations between hip fracture outcome and risk factors in clinical databases. In general, these tools are good for studying epidemiology of osteoporotic fracture in large populations, but have limited accuracy for assessing fracture risk in individual subjects, which is a common drawback of statistical models. In contrast, the biomechanical models such as finite element models still have very limited clinical application, even though they have sound mechanical basis and are theoretically superior to the population-based tools for predicting fracture risk in individuals. The main challenge is that hip fracture resulting from low-trauma accidental fall is a complicated dynamics and impact process involving a number of biomechanical variables that span over multiple length scales (or body levels), ranging from the whole-body-level kinematics and kinetics to bone failure at the microscopic level. None of the existing single-level biomechanical models is able to consider all the variables. To accommodate the variables, we developed an image-based three-level biomechanical model [15]. In this paper, we report the results that the three-level model was applied to discriminate clinical hip fracture cases from matched controls, a prerequisite study before the model can be transferred into a clinical tool.

IMAGE-BASED THREE-LEVEL BIOMECHANICAL MODEL

The three-level model consists of a whole-body dynamics model, a proximal-femur finite-element (FE) model, and a bone local failure model. Figure 2 shows the relations among the three models and the main biomechanical variables considered in each model. In

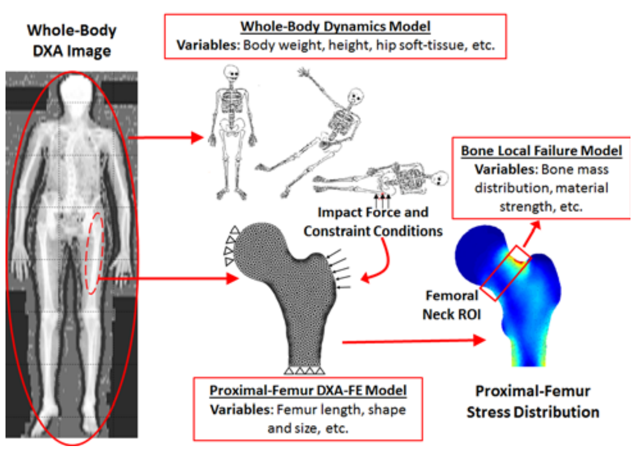

Figure 2 Three-level biomechanical modeling of fall-induced hip fracture

principle, the models can be constructed from either dual energy X-ray absorptiometry (DXA) or quantitative computed tomography (QCT). DXA is currently the primary imaging modality in clinic and will remain so in the foreseeable future [16], therefore we only consider DXA-based models in this paper. The construction of the models is briefly described in the following sections.

Whole-Body Dynamics Model for Simulation of Sideways Fall and Prediction of Impact Force

More than 95% of hip fractures are caused by low-trauma falls such as a sideways fall from standing height [17]. The impact forces induced during a fall often have a large magnitude, and may also produce abnormal stress patterns that are unfavorable for the femur to resist. For example, in a sideways fall, the superior side of femoral neck has to withstand compressive stresses, but the region is dominated by cancellous bone that has been adapted to resist tensile stresses. An effective way to predict impact forces experienced by elderly people in a fall is by image-based dynamics simulation [8, 15, 18]. We developed and experimentally validated a three-link dynamics model to predict impact force in sideways falls [8, 19]. The construction of a dynamics model from whole-body DXA image of a concerned subject is illustrated in Figure 2. First, the anthropometric and dynamics parameters

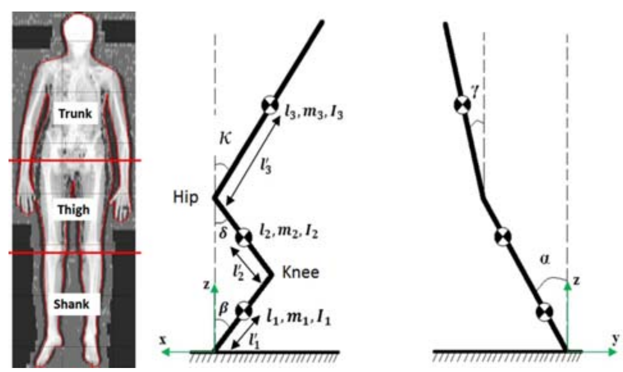

Figure 1 Construction of whole-body dynamics model

required by the model are extracted from the DXA image. Dynamics governing equations are derived using the Lagrange principle. Fall kinematics such as hip velocity before impact is determined by dynamics simulation. The impact force is predicted based on the simulated kinematics and dynamics variables [8]. Consider that whole-body DXA may not always be available, we also constructed a set of empirical functions using dynamics simulation data, to estimate impact force in a sideways fall

[20]. Variables required by the empirical functions include the subject's body weight, height and thickness of hip soft-tissue.

<u>DXA-based proximal-femur FE model for computing femur stress induced by impact force</u>

Femur stresses induced by impact force decide whether and where a fracture will occur on the femur. For the complexity of femur geometry and inhomogeneity of bone mechanical properties, finite element (FE) analysis is commonly applied to determine the stresses. Various proximal-femur FE models have been developed for this purpose. We developed a DXA-based subject-specific FE model on the basis of the plane stress theory of material mechanics [15]. The steps for constructing a DXA-based FE model is shown in Figure 3. The procedure starts with a hip DXA image of the concerned subject, see Figure 3(a). The contour of the femur is segmented by an automated algorithm, and a finite element mesh is generated, Figure 3(b). Bone mechanical properties in the finite elements, e.g. Young's modulus, are assigned based on bone density information, Figure 3(c). Loading and constraint conditions simulating a sideways fall are applied to the finite element model, Figure 3(d). The impact force acting on the great trochanter is determined by either dynamics simulation or empirical function described in the previous section. Stress distribution in the femur is obtained by a finite element analysis, Figure 3(e).

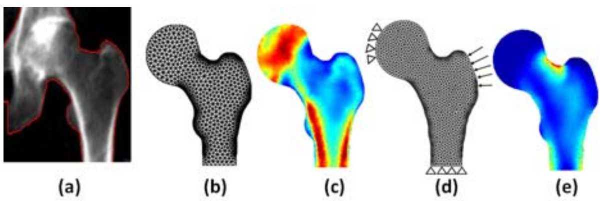

Figure 3 Finite element analysis of femur stress induced by impact force

<u>Bone local failure models for evaluation of femur integrity</u>

With stress distribution in the affected femur, integrity of the bone can be evaluated based on the principle of material strength, i.e. if the stresses at a specific location exceeds bone allowable stress, a crack will be initiated and hip fracture will occur. Bone ultimate stress is determined by bone density. We introduced a site-specific criterion to evaluate femur integrity [21]; The criteria is expressed as fracture risk index (FRI), the ratio of stress induced by impact force to the allowable stress of bone in clinical regions of interest, e.g. the femoral neck and intertrochanter, where the majority of hip fractures have been observed [22]. If FRI≥1, it indicates a high risk of hip fracture.

CLINICAL STUDY AND RESULTS

From the Manitoba Bone Mineral Density (BMD) Database, we identified 99 prior hip fracture cases and 294 non-fracture controls. All subjects were women with age ≥ 65 years and hip T-scores below -1, and had no osteoporosis treatment. All hip DXA were scanned by Prodigy, GE Healthcare. For each subject, femoral neck (FN), intertrochanteric (IT) and subtrochanteric (ST) FRIs were calculated using the three-level model. As whole-body DXA was not available, impact forces were estimated using the empirical functions [20]. Area under the ROC curve (AUC) and odds ratio (OR), both with 95% confidence interval (CI), were used to measure the discriminability of a method. The obtained results are provided in Table 1.

Table 1: AUC (95% CI) and OR (95% CI) of femoral BMD and FRI at femoral neck (FN), intertrochanter (IT) and subtrochanter (ST)

	AUC (95% CI)	**OR (95% CI)**
FN BMD	0.713 (0.647, 0.780)	2.27 (1.72, 3.00)
FN FRI	0.713 (0.649, 0.777)	2.47 (1.78, 3.43)
IT FRI	0.780 (0.724, 0.836)	4.40 (2.68, 7.21)
ST FRI	0.750 (0.690, 0.811)	3.07 (2.13, 4.43)

The results show that there was significant association between hip fracture and FRI at the three sites on femur. In general, all FRI had better performance than femoral neck BMD in discriminating fracture cases from controls. Intertrochanteric FRI had the best performance (AUC=0.780), suggesting that the majority of the fractures are intertrochanteric fracture. Intertrochanteric fractures are most common based on clinical study [22]. The intertrochanteric region is dominated by cancellous bone, which has much lower strength than cortical bone, and the region is directly impacted with the ground in a sideways fall.

CONCLUSIONS

Femoral neck BMD is currently considered as the gold standard for screening osteoporosis and predicting fracture risk. This study suggests that the three-level biomechanical model is potentially a better method for predicting hip fracture risk than femoral neck BMD. The reason is that the biomechanical model considers fall-induced impact force, femur geometry and bone quality, all of them are determinants of hip fracture but not all of them are included in BMD.

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