A combined experimental and computational approach to study impacts to the hip from sideways falls with an advanced pendulum fall simulator

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I. INTRODUCTION

Hip fracture in the elderly is the most devastating injury amongst osteoporotic fractures, posing a high risk of morbidity and mortality. State-of-the-art screening methods, based on areal bone mineral density (aBMD), capture less than half of hip fracture cases [1]. The main focus of fracture risk predictions has so far been on the load-bearing capacity of the femur, neglecting important aspects like the risk of falling and the load the femur of a specific person would experience during a fall. Estimating these loads is not possible in vivo due to the obvious fracture risk. Therefore, injurious loads can only be studied with ex-vivo specimens or computational or physical models. Cadaveric impact models simulating a sideways fall loading have modelled non-subject-specific loads, neglected the influence of soft tissue [2] Most studies also neglected the influence of pelvis deflection and the inertially driven nature associated with a sideways fall [3,4]. Other side impact loading conditions, representative of a side impact motor vehicle collision, have also been studied using full body cadavers, but have failed to create femoral fractures [5]. We hypothesized that, by subjecting femur-pelvis units of post mortem human subjects (PMHS) to boundary conditions (including those associated with pelvis deformation), dynamics and input energy representative of a fall to the side from standing height, we would create clinically observed femoral fractures, pelvic fractures and also observe non-fractures. We further hypothesized that aBMD would not be a good predictor of fracture outcome when considering subject-specific loads for falls to the side. Finally, we postulated that explicit finite elements (FE) can predict impact and fracture outcome for these types of falls.

II. METHODS

Eleven pelvis-femur constructs from elderly PMHS were embedded in subject-specific surrogate soft tissue material (ballistic gelatine) moulded to simulate the volumes and shapes of the specific tissue donor. Each specimen was subjected to a controlled inverted pendulum motion with impact to the greater trochanter. The greater trochanter metallic lower limb constructions, with subject-specific mass, were used to represent the human body from mid-femur down to the feet. The impact kinetics and kinematics were recorded with a force plate (Bertec, Columbus, OH, USA) at 10,000 Hz and a stereo high-speed camera system (Phantom v12, Vision Research, Wayne, NJ, USA) at 5,000 Hz. Fracture outcomes were determined based on post-testing planar x-ray images and specimen aBMD was determined based on quantitative CT using a validated commercial tool (QCT Pro, Mindways, Austin, Texas).

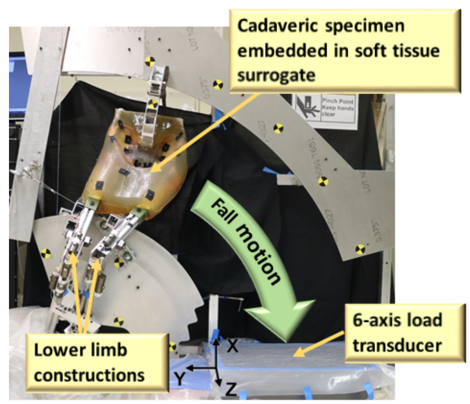

Fig. 1. Inverted pendulum setup to mimic sideways fall impact.

dissections. For each specimen,

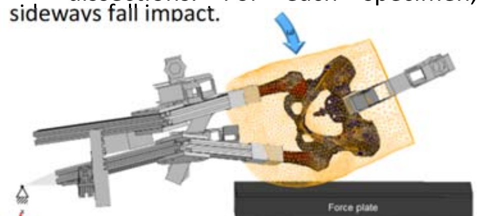

Fig. 2. Dynamic FE model of sideways falls with boundary conditions based on the

Subject-specific explicit FE models were created based on each experiment. Bone geometries and density information were extracted from quantitative CT, using an intensity to bone density conversion based on hydroxyapatite phantoms. Heterogeneous material properties with yield and post-yield behaviour [6] were mapped for bone based on the CT grey levels. Quadratic tetrahedral elements with an edge length of three mm were used for the

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impacted femur. Linear tetrahedral elements were used for the pelvis and contralateral femur, as well as other tissues. The cortical and trabecular compartments were not modelled separately. Cartilage and ligaments modelling was based on the geometry of bones and anatomic literature. Non-linear material properties were applied according to literature. Specimen alignment and boundary conditions were applied based on experimental conditions just prior to first contact with the impact surface. Geometries, masses, and mass were adjusted to measurements that were recorded prior to testing. The geometry of the soft tissue was matched based on the original CAD shape and digitized points. No further drivers were applied to the FE model and no parameters in the model were optimized to better match the experimental outcome.

III. INITIAL FINDINGS

Three non-fractures, five femur fractures and four pelvic fractures, one of which also resulted in femur fracture, were observed experimentally. The peak forces measured at the impact surface varied from 2910 N to 7601 N, and the time to peak force from 4.0 ms to 28.8 ms. aBMD alone was not a good predictor of fracture outcome, as shown in Fig. 3(a). Five experiments (three femoral fractures and two non-fractures) have been modelled with FE thus far. The predicted peak impact force for the experiment and the FE are shown in Fig. 3(b). The FE matched the experimental results very well, with a root mean square error (RMSE) of 13% and a correlation of R^2 = 0.93. Similar results were obtained for the time to peak force (RMSE=25%, R^2 = 0.96). The fracture outcome predicted by the FE model matched the experimental outcome for all five specimens.

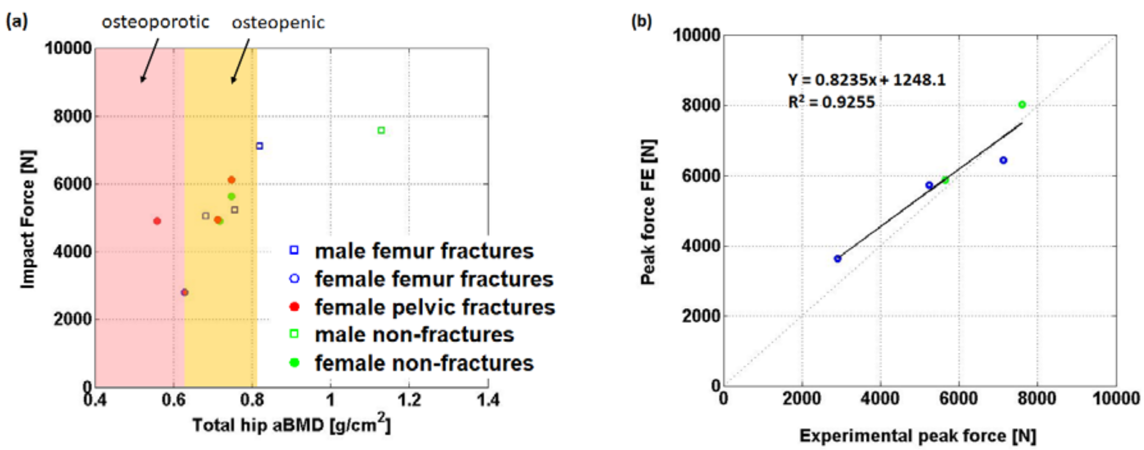

Fig. 3. (a) Impact force vs areal bone mineral density with fracture outcomes, (b) peak impact force for the FE vs the peak impact force for the experiment. Femoral fractures in blue, non-fractures in green.

IV. DISCUSSION

This study presents a novel impact model, which is the first to produce femoral and pelvic fractures, as well as non-fractures, that are representative of a fall to the side in the elderly. Non-fractures are also a common outcome of a fall to the side [7]. We document the dependency of the impact impulse on the soft tissues surrounding the pelvic region and, to our knowledge, we are the first to report impact loads up to injurious force levels for falls to the hip from standing height in an inertially driven pendulum model. Further, a novel FE modelling method is presented, which accurately predicts the kinetics and kinematics of the experiment as well as the fracture outcome. aBMD alone failed to differentiate fractures from non-fractures. These models can be used to investigate internal forces and force transmission, load-sharing and energy transfer at the hip joint and surrounding anatomy. In future studies, these types of models can be used to better understand anthropometric, bone quality, and bone density parameters influencing the risk of hip fracture. Further, population cohort studies will show if these models can help to create better predictors for fracture risk in the elderly.

V. REFERENCES

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