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Technical note

Development of a balanced experimental–computational approach to understanding the mechanics of proximal femur fractures

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ABSTRACT

The majority of people who sustain hip fractures after a fall to the side would not have been identified using current screening techniques such as areal bone mineral density. Identifying them, however, is essential so that appropriate pharmacological or lifestyle interventions can be implemented.

A protocol, demonstrated on a single specimen, is introduced, comprising the following components; in vitro biofidelic drop tower testing of a proximal femur; high-speed image analysis through digital image correlation; detailed accounting of the energy present during the drop tower test; organ level finite element simulations of the drop tower test; micro level finite element simulations of critical volumes of interest in the trabecular bone.

Fracture in the femoral specimen initiated in the superior part of the neck. Measured fracture load was 3760 N, compared to 4871 N predicted based on the finite element analysis. Digital image correlation showed compressive surface strains as high as 7.1% prior to fracture. Voxel level results were consistent with high-speed video data and helped identify hidden local structural weaknesses.

We found using a drop tower test protocol that a femoral neck fracture can be created with a fall velocity and energy representative of a sideways fall from standing. Additionally, we found that the nested explicit finite element method used allowed us to identify local structural weaknesses associated with femur fracture initiation.

1. Introduction

There is ample evidence showing that the majority (>90%) of fragility related hip fractures are associated with a sideways fall from standing height. While falls in older adults are common [1], only 1–5% result in a fracture [2–4], with falls to the side having the highest fracture rate [5]. The majority of people who sustain hip fractures after a fall to the side would not have been identified using current screening techniques such as areal bone mineral density (aBMD) [6], however, this is essential so that appropriate pharmacological or lifestyle interventions can be implemented.

In the experimental in vitro studies of a sideways fall in the past, force has most often been applied on the specimens using materials testing machines [7–11] with the femoral head and shaft supported while the actuator of the machine displaces the greater trochanter. Two aspects of this method limit its capacity to represent a sideways fall. First, loading rates of 0.1 m/s or lower have been generally used, while the impact speed associated with a sideways fall from standing is 3.0 m/s or higher [12,13]. The second limitation is that load has been generally increased monotonically until fracture occurs, which probes the load carrying capacity of a femur on its side, rather than investigating fracture in a sideways fall scenario. Fall simulation experiments, where the specimens are impacted with a mass dropped from a height that produces impact energy representative of a fall on the side from standing height, have the potential to address these limitations.

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Subject-specific finite element (FE) analysis based on X-ray computed tomography (CT) scans for studying the mechanics of the proximal femur have been extensively published in the literature [8,10,11,14–24]. These models have been tested under a variety of loading configurations and material mapping techniques; however, they have almost invariably followed a quasi-static structural approach and been validated against quasi-static in vitro models. There are limitations of disassociating the fall event from the calculations of the structural integrity of the bone; for example, neglecting the influences of rate dependence, and the inertia of the body. The effect of these properties can be generally quantified by including calculation of the work energy throughout the failure event.

The aim of the present study is to introduce a multi-modality protocol that addresses some of the aforementioned limitations of previous studies on hip fractures. The protocol comprised the following components; (a) in vitro biofidelic drop tower testing of donor specimens at fall speeds; (b) high-speed imaging analyzed with digital image correlation (DIC) to determine surface strains, which will be used to validate FE models; (c) detailed accounting of the energy present during the drop tower test based on impact load cell and high speed imaging data; (d) organ level numerical simulations of the drop tower test; and (e) micro level simulations of critical volumes of interest.

We report results from a single specimen that failed in compression in the superior part of the femoral neck. This case is ideal for highlighting some of the limitations of the state of the art knowledge in hip fracture mechanics and, by contrast, the strengths associated with our approach.

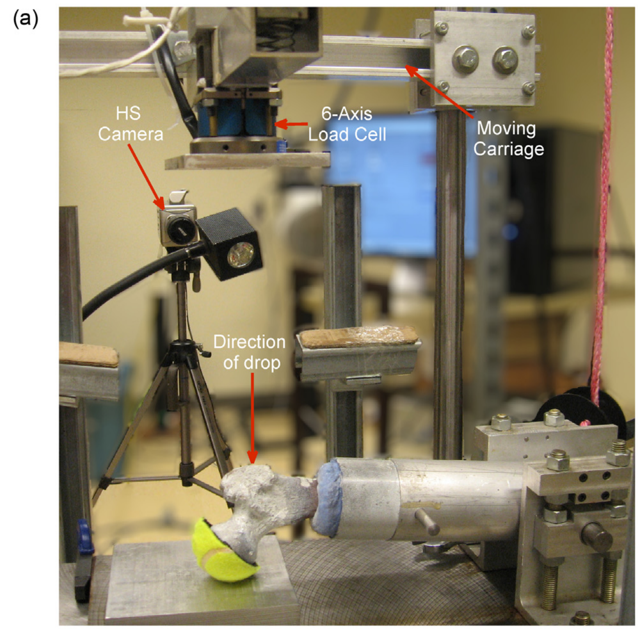
2. Materials and methods

2.1. Drop tower test

One fresh-frozen human femur specimen (female, 85 years, 40 kg) was thawed, its shaft sectioned at mid-thigh and potted in an aluminum cylinder using polymethylmethacrylate (PMMA, Bosworth Co., Skokie, IL) (Fig. 1). The specimen was positioned in accordance with Courtney et al. [25] and the femoral head placed in a sectioned tennis ball to avoid crushing of the head during impact. A 16.5 kg impactor, incorporating a 6-axis load cell (Denton model 4366J, Rochester Hills, MI, 25 kN, 90 kHz) mounted on a carriage with linear bearings, was dropped from a height of 0.624 m onto the greater trochanter, aiming to produce an impact speed of 3.5 m/s and impact energy of approximately 103 J, representative of energies released in a sideways fall [12,13]. The time of contact between the impactor and the trochanter's PMMA cap was defined as $t = 0$. Two high speed cameras (Phantom V9.1, Vision Research Inc., NJ, USA, 9009 frames/second) recorded the proximal femur anteriorly and posteriorly at a resolution of 384 × 384 pixels and an approximate pixel pitch of 0.25 mm.

2.2. Digital image correlation

Images from the cameras were exported as bitmaps into DaVis and StrainMaster (v8, LaVision, Goettingen, Germany). DaVis was used to remove rigid body translations and rotations, and then correlations were performed in regions where the bone surface was angled less than approximately 25° from the camera lens axis. Three correlation passes using 32 × 32 pixel interrogation regions, with 50% overlap and error checking between, were used. Each image was compared to the first image in the series, and minimum principal strain was extracted in post processing.



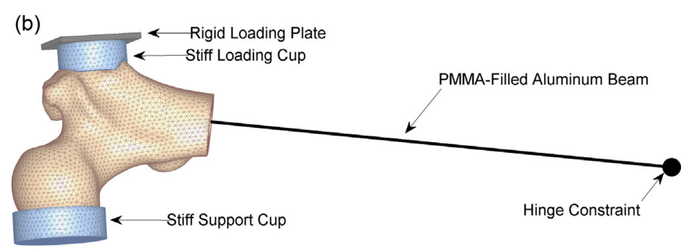


Fig. 1. (a) Experimental drop tower setup. The jig allowed rotation in the frontal plane and translation in the sagittal plane. A PMMA pad (not shown) was used to distribute the impact force over the greater trochanter. The femur surface was covered with a speckle pattern that served as reference for DIC; (b) the organ level FE model was constrained distally with a pivot, to correspond to the experimental setup. The pivoting point was connected to the shaft with beam elements. The mass and cross sectional properties of these elements were set to that of the PMMA-filled aluminum cylinder. The surface area of the medial femoral head was constrained against vertical translation but allowed to move freely in all other directions. Sliding contact surfaces to support the femoral head and apply displacement at the greater trochanter. Meshes with average edge lengths of 6, 4, 3, and 2 mm were created and solved using the described methodology. Force peaks and stiffness were found to converge with increasing mesh density. A model with 3 mm average edge length (47,467 10-node parabolic solid elements and 70,484 nodes) was selected, as its force peak and stiffness results differed by only around 2% from the denser 2 mm mesh.

2.3. Energy balance of the drop tower test

The following equation describes the energy balance of our drop tower setup at any time t after initial contact and before the femur fractures or stops the falling mass:

$$mg(h + u_f + u_s) = \int f_f(u_f)\,du + \int f_s(u_s)\,du + \frac{1}{2}mv^2 + W_{\mathrm{res}} \qquad (1)$$

where m, the dropped mass (16.5 kg); g, acceleration of gravity (9.81 m/s^2); h, drop height (0.624 m); u_f, femur displacement; u_s, displacement of the femoral head support; $f_f(u_f)$, force–displacement relationship at the greater trochanter; $f_s(u_s)$, force–displacement relationship at the femoral head support; v, instantaneous speed of the greater trochanter $(d(u_f + u_s)/dt)$; W_{res}, residual energy such as the kinetic energy gained by the femur, noise, deformation of the drop tower, damping and friction. u_f, u_s, f_f, f_s, v, and W_{res} all vary with time t.