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Proximal femur elastic behaviour is the same in impact and constant displacement rate fall simulation

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ABSTRACT

Understanding proximal femur fracture may yield new targets for fracture prevention screening and treatment. The goal of this study was to characterize force–displacement and failure behaviours in the proximal femur between displacement control and impact loading fall simulations. Twenty-one human proximal femurs were tested in two ways, first to a sub-failure load at a constant displacement rate, then to fracture in an impact fall simulator. Comparisons of sub-failure energy and stiffness were made between the tests at the same compressive force. Additionally, the impact failure tests were compared with previous, constant displacement rate failure tests (at 2 and 100 mm/s) in terms of energy, yield force, and stiffness. Loading and displacement rates were characterized and related to specimen stiffness in the impact tests. No differences were observed between the sub-failure constant displacement and impact tests in the aforementioned metrics. Comparisons between failure tests showed that the impact group had the lowest absorbed energy, 24% lower maximum force and 160% higher stiffness than the 100 mm/s group ($p < 0.01$ for all), but suffered from low statistical power to differentiate the donor age and specimen BMD. Loading and displacement rates for the specimens tested using impact varied during each test and between specimens and did not show appreciable viscoelasticity. These results indicate that constant displacement rate testing may help understand sub-failure mechanical behaviour, but may not elucidate failure behaviours. The differences between the impact and constant displacement rate fall simulations have important ramifications for interpreting the results of previous experiments.

1. Introduction

Hip fracture is a devastating injury associated with high mortality, morbidity, and high economic costs, on both personal and social levels (Braithwaite et al., 2003; Wiktorowicz et al., 2001). One of the critical avenues for reducing the burden of hip fracture has been early identification of potential hip fracture patients (Johnell et al., 2005; Kanis et al., 2009; van den Bergh et al., 2010). Clinically, early identification is done using areal bone mineral density (aBMD) as measured by dual-energy X-ray absorptiometry (DXA); however, this technique captures fewer than 30% of those who suffer hip fracture (Stone et al., 2003). One factor that may contribute to this discrepancy is a lack of understanding of the mechanism of hip fracture. Increased understanding of the fracture mechanics of the proximal femur could aid the development of specific and sensitive tools for identifying people at risk of hip fracture.

Biomechanical researchers have utilized mechanical testing and computational modelling to study how the proximal femur fails in a fall to the side (Keyak et al., 1998; Keyak and Rossi, 2000; Verhulp et al., 2006, 2008; Srinivasan et al., 2011; Koivumäki et al., 2012). These researchers have identified the roles of bone density (Lotz and Hayes, 1990; Courtney et al., 1995; Leichter et al., 2001; Lochmüller et al., 2002; Eckstein et al., 2004; Boehm et al., 2008; Manske et al., 2008; de Bakker et al., 2009; Pulkkinen et al., 2008), posture (Pinilla et al., 1996), displacement and strain rate (Weber et al., 1992; Courtney et al., 1994), geometry (Cheng et al., 1997), and loading configuration (Keyak et al., 1998; Keyak, 2000). While these studies have contributed greatly to the current

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understanding of hip fracture, they used constant displacement rate protocols. There may be differences in the mechanics of the proximal femur in an impact loading situation that would affect interpretation of the previous results.

In a fall to the side, the displacement rate of the proximal femur is not prescribed or constant. Instead, it is dictated by the dynamics of the fall and the response of the body under impact. The femur acts as a compliant member in a spring-mass system which includes the body, the pelvis, and soft tissues surrounding the femur. During the fall, the instantaneous value of a femur's compliance influences its displacement rate (in mm/s) and loading rate (in N/s), which in turn alters the bone's mechanical behaviour in a rapid and complex way (Carter and Hayes, 1977; Linde et al., 1991). We believe that the recursive nature of this relationship makes it essential to model the fall in order to measure and visualize the actual progression of failure of the proximal femur. Because the femur has not been previously studied under these conditions, it is not known if the behaviour or mechanics of the femur is different between the historical laboratory simulations and real-world falls to the side.

The objectives of this research were to: (i) determine if femoral deformation is different between constant displacement rate and impact testing; (ii) determine if femoral failure characteristics are different between the two loading methods; and (iii) characterize the free-response force and displacement curves in a biofidelic impact. We hypothesized that the proximal femur's sub-failure force–displacement behaviours would be different between low displacement rate loading and impact fall simulation. Further, we hypothesized that the proximal femurs' failure mechanics would be different between fixed displacement rate and fall simulation failure tests.

2. Materials and methods

Three groups of specimens were used in this analysis. Two groups consisting of 29 specimens were those tested by de Bakker et al. (2009) and Nishiyama et al. (2013) in our lab under constant displacement rates (Table 1). An additional 21 specimens were tested in combined high sub-failure+impact fall simulation protocol. The research was approved by the University of British Columbia and University of Calgary research ethics boards. In this document the specimens will be referred to by how displacement was applied; those from Nishiyama et al. (2013) will be referred to as the *slow* group; those from de Bakker et al. (2009) will be referred to as the *fast* group; and the specimens in the current test will be referred to as the *fall* group because they were failed using the fall simulator. Each specimen in the fall group was subjected to two test conditions, a quasi-static, constant displacement rate, sub-failure test (fall:QS) and an impact fall simulation failure test (fall:FS). There were no detectable differences in terms of age (Student's *t*-test results and power to detect an age difference of 10 years for fast: $p=0.10$, $1-\beta=0.81$, and slow: $p=0.90$, $1-\beta=0.87$) or gender (chi-squared test results and power to detect a doubling of the male:female ratio for fast: $p=0.59$, $1-\beta=0.41$, and slow: $p=0.20$, $1-\beta=0.81$), but the aBMDs of the slow and fast groups were different. Examining the aBMDs showed that the fall groups' were between those of the other groups and were not significantly different than either (Student's *t*-test results and power to detect a difference of 0.15 g/cm^2 for fast: $p=0.19$, $1-\beta=0.69$, and slow: $p=0.12$, $1-\beta=0.49$). No comparisons are made in this study between the fast and slow groups.

Table 1
Specimen groups showing identifying characteristics. The slow (Nishiyama et al., 2013) and fast (de Bakker et al., 2009) groups are discussed in more detail in previous publications. The specimens in Fall:QS and Fall:FS are from the same specimens population, but include different specimens based on data availability. Comparisons between these two groups were restricted to specimens tested using both methods. Numbers are shown as mean (standard deviation).

Group	Age (years)	Number and gender	aBMD (g/cm^2)	Displacement rate (mm/s)	Loading rate (kN/s)
Slow	77 (13)	4 M, 14 F	0.613 (0.164)	2	0.5 (0.16)[a]
Fast	84 (7)	6 M, 5 F	0.763 (0.150)	100	33 (8)[a]
Fall: QS	77 (10)	1 M, 19 F	0.707 (0.108)	0.5	0.22 (0.16)[a]
Fall:FS	77 (11)	2 M, 15 F	0.694 (0.113)	114 (53)[a]	150 (35)[a]

[a] While these numbers are results of the tests and not set a priori, they are presented here to illustrate the differences between groups.

All specimens were fresh frozen human proximal femora. The slow and fast groups' preparations were discussed in detail in their respective publications (de Bakker et al., 2009; Nishiyama et al., 2013). Their treatments were similar to the fall group specimens except for application of paint for digital image correlation (DIC) and a different protocol for setting the length from the head to the pivot in the fast group. The fast group's head to pivot length was set to two-third of the full specimen length whereas the slow and fall groups' lengths were set to a fixed value discussed below. The specimens in the fall group were cleaned of soft tissue and periosteum, and a white-speckle on black-background pattern was painted onto the anterior-superior neck using an airbrush (VL, Paasche, Chicago, IL) to facilitate DIC measurement of surface strains (Gilchrist et al., 2014). The specimens were imaged using dual-energy X-ray absorptiometry (DXA) (QRD 4500W, Hologic, Bedford, MA) with 4 kg rice to simulate soft tissue (Sran et al., 2004), and high-resolution, planar X-ray (FCR Capsula X, Fujifilm, Tokyo, Japan).

The fall:QS tests were sub-failure, quasi-static, constant displacement rate tests performed to characterize the mechanical behaviours of the femurs in a scenario similar to the tests performed in the previously published literature (Fig. 1). The tests were carried out in the standard fall configuration of 10° adduction and 15° internal rotation of the femoral neck (Courtney et al., 1994; de Bakker et al., 2009; Manske et al., 2008), with the distance from the pivot to the farthest point on the specimen in the range of 290–305 mm. Two polymethylmethacrylate (PMMA, Bosworth Co, Skokie, IL) caps were made, one for the lateral trochanter, and one for the medial femoral head, formed to have parallel surfaces. A materials testing machine (8874 Instron, Norwood, MA) was used to apply a 100 N preload over 5 s, which was held for 0.5 s. Then the specimens were loaded to 50% of their total-aBMD predicted failure loads (Boehm et al., 2008) at 0.5 mm/s, held for 2 s, then unloaded. After testing, the bones were imaged with the planar X-ray. Force and displacement data were collected at 20 kHz (PCI-6040E, National Instruments, Austin, TX).

The fall:FS tests were conducted to failure in the same orientation, mounting apparatus, and potting as the fall:QS tests, but in a fall simulator (Fig. 2) which we have previously described in detail (Gilchrist et al., 2014). Briefly, the simulator consisted of a drop tower with elements to replicate the mechanical effects of various anatomical elements surrounding the proximal femur including the body mass (32 kg), mass of the lateral pelvis and proximal femur (1.98 kg), pelvis stiffness (50 N/mm), and trochanteric soft tissue (19 mm foam). Force data were collected at 20 kHz from a ± 13.34 kN, six-axis load cell (Denton 4366J, Humanetics, Plymouth, MI) with a full range non-linearity of <130 N. The axial force signal was amplified such that voltage saturation would be obtained at 6 kN. Displacements were obtained using a high speed camera (Phantom V9, displacement camera in Fig. 2) recording at 9216 Hz with an in-plane resolution of 576×288 pixel (5 pixel/mm) that imaged both the impact hammer and the potting over the greater trochanter.

Specimen displacement was corrected for machine compliance. The compliances of the materials testing machine and the fall simulator were measured directly by applying known loads to the frames and measuring the resulting displacements. For the slow, fast, and fall:QS groups specimen displacement was calculated by subtracting machine displacement from the loading platen displacement. For the fall:FS group a first order, single degree of freedom, dynamic model of the frame was used to estimate machine displacement, which was subtracted from the trochanter displacement. The dynamic model was used because static calculation overestimated the displacement in the initial milliseconds of the impact test.

In the slow, fast, and, fall:QS groups, stiffness was calculated as the slope of the force vs. displacement curve between 25% and 75% of the yield force. In the fall:FS group stiffness was calculated between 25% and 90% of the yield force, where yield was defined as the point at which the force–displacement curve first deviated from linear. These ranges were chosen because they reliably captured the linear region of

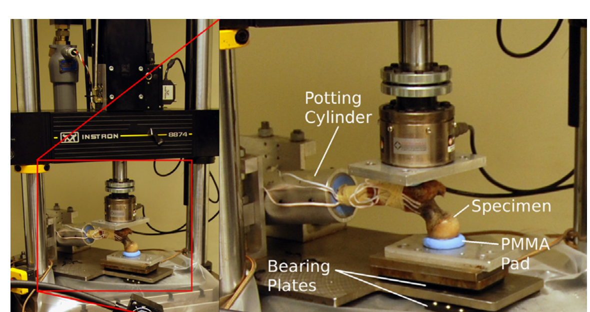

Fig. 1. The materials testing machine used for the fast, slow, and fall:QS loading experiments.