Orthopedic Surgical Forum

Effects of Loading Rate on Strength of the Proximal Femur

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Received: 18 November 1993/ Accepted: 27 December 1993

Abstract: Results from previous quasi-static mechanical tests indicate that femurs from elderly subjects fail in vitro at forces 50% below those available in a fall from standing height. However, bone is a rate-dependent material, and it is not known whether this imbalance is present at rates of loading which occur in a fall. Based on recent data on time to peak force and body positions at impact during simulated falls, we designed a high rate test of the femur in a loading configuration meant to represent a fall on the hip. We used elderly (mean age 73.5 ± 7.4 (SD) years) and younger adult (32.7 ± 12.8 years) cadaveric femurs to investigate whether (1) the strength, stiffness, and energy absorption capacity of the femur increases under high rate loading conditions; (2) elderly femurs have reduced strength, stiffness, and energy absorption capacity compared with younger adult femurs at this loading rate; and (3) densitometric and geometric measures taken at the hip correlate with the measured fracture loads. Femurs were scanned using dual-energy X-ray absorptiometry (DXA) and then tested to failure in a fall loading configuration at a displacement rate of 100 mm/second. The fracture load in elderly and younger adult femurs increased by about 20% with a 50-fold increase in displacement rate. However, energy absorption did not increase with displacement rate because of a twofold increase in stiffness at the higher loading rate. Age-related differences in strength and energy absorption capacity were consistent with those found previously for a displacement rate of 2 mm/second. There were moderate to strong correlations between fracture load and DXA variables, with the best correlation provided by cross-sectional area (r² = 0.77) and bone mineral density (BMD) (r² = 0.72) at the femoral neck. Our results indicate that, even at rates of loading applied during a fall, the estimated impact force in a fall on the hip is 35% greater than the average fracture load of the elderly femur. Moreover, the relationship we found between femoral neck BMD and fracture load indicates that an increase in femoral neck BMD of more than 20% would be required to raise the strength of the femur to the level of the impact load. As clinical trials of pharmacologic interventional treatments have demonstrated increases in BMD of only a few percent at best, our results emphasize the continuing need for intervention strategies that focus on full prevention and on reducing the severity of those falls that do occur.

Key words: Hip fractures — Femoral strength — Rate sensitivity — Aging — Dual X-Ray absorptiometry.

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Elderly individuals face a 20% chance of death and a 50% chance of long-term disability as a result of a hip fracture [1]. More than 280,000 hip fractures occur each year in the United States alone, and 90% of these fractures occur in persons over age 65 [2]. In the U.S., the number of people over age 65 is already greater than the entire population of Canada, and each day 6000 more people celebrate their 65th birthday [3]. Hip fractures account for more hospital days than any other musculoskeletal injury and represent more than two-thirds of all hospital days due to fractures [2].

Hip fractures are thought by most to be primarily the sequelae of osteoporosis [4, 5]. This view is consistent with age-related decreases in bone strength [6] and increases in hip fracture incidence [1, 7]. However, measures of bone density have not clearly or consistently distinguished between elderly hip fracture subjects and nonfractured controls [5]. In addition, more than 90% of hip fractures are caused by a fall [7, 8], suggesting that falling, rather than osteoporosis, may be the dominant risk factor for hip fracture. Recent data from a fall surveillance study of community-dwelling elderly, in which measures of both bone density and fall characteristics were available, support the view that both are important determinants of hip fracture risk [9]. Using a multiple regression model, Greenspan et al. found that a fall to the side, reduced bone density, lowered body mass, and increased potential energy of the fall were all independent predictors of hip fracture in elderly fallers [9].

We have shown from quasi-static tests that the elderly femur is only half as strong and absorbs only one-third as much energy as the younger adult femur [10]. In addition, the average elderly femur consistently fails in vitro at forces and energies below those available in a fall from standing height [10–12]. In light of these data, it is surprising that the incidence of hip fracture among the elderly is not much higher than it is. One obvious explanation for this discrepancy is that most falls are not to the side. A second possibility is that previous quasi-static studies have underestimated the strength of the elderly proximal femur, which could be stronger under higher rates of loading.

Previous mechanical tests of the femur under conditions simulating a fall on the hip have not reflected information on the loading configuration and displacement rate applied to the femur in a fall. Based on recent data on time to peak force [13] and body positions [14] at impact during simulated falls, we designed a high rate test of the femur in a fall loading configuration. We used both elderly and younger adult cadaveric femurs to determine whether: (1) the strength, stiffness, and energy absorption capacity of the femur increases under high rate loading conditions; (2) the strength,
stiffness, and energy absorption capacity of the elderly femur are less than that of the younger adult femur at this loading rate; and (3) densitometric and geometric measures taken at the hip correlate with the measured fracture loads.

Materials and Methods

Human femurs from 10 elderly donors of mean age 73.8 ± 7.1 (SD) years (four females, six males) were obtained from the local anatomic gifts program using standard protocols. Femurs from 10 younger donors of mean age 31.7 ± 12.5 (SD) years (three females, seven males) were obtained from local tissue banks. All specimens were fresh and stored frozen at −20°C, and were thawed to room temperature prior to testing. Femurs were kept moist with saline throughout thawing, preparation, and testing. A radiograph of each pair of femurs was taken at 80 KV and 3 ma for 20 seconds with the anterior surface of the bone in contact with the X-ray film. Femoral neck width and hip axis length were measured with digital calipers from the X-ray films. Hip axis length was defined as the length of the line bisecting the femoral neck along its axis, measured from the supero-medial aspect of the femoral head to the lateral aspect of the greater trochanter.

Dual energy X-ray absorptiometry (DXA) scans were performed using the pencil-beam mode of a Hologic QDR-2000 densitometer (Hologic Inc., Waltham, MA). A single, anteroposterior scan was taken with the femur submerged in room temperature saline and secured distally with the neck parallel to the table. Standard clinical measurements of areal bone mineral density (BMD, g/cm²) and bone mineral content (BMC, g) were taken for the neck and trochanteric regions. Data for each femur were compared with those from a database of "normal" individuals to dem-

The scan data from the QDR-2000 were postprocessed using software developed in our laboratory to obtain attenuation values for cross-sections at the femoral neck and trochanteric regions [16, 17]. The femoral neck cross-section was defined by the plane perpendicular to the neck axis at the midneck location; the intertrochanteric cross-section was defined by the bisection of the biconcave plane and a line at the inferior aspect of the lesser trochanter made perpendicular to the diaphyseal axis. The projected cross-sectional area (cm²) and moment of inertia (Iyy, cm⁴) for each cross-section were obtained by integrating the attenuation curves.

For mechanical testing, femurs were positioned to simulate a fall on the greater trochanter (Fig. 1). The configuration was similar to one used by Backman [18] which produced clinically realistic fracture types, and to that used by Lotz and Hayes [11] for fracture tests of elderly femurs. The loading configuration was refined using data from a recent study of experimental falls showing typical body positions at impact [14]. The angle of the femoral shaft was 10° with respect to the horizontal, and the femoral neck was internally rotated 15°. The femurs were free to rotate in the vertical plane and to translate in the horizontal plane, but were fixed distally against rotation about the diaphyseal axis. The femoral head fit into a polyethylene acetabulum. The greater trochanter was supported by polymethylmethacrylate in a hemispherical steel shell to prevent local crushing of the greater trochanter and to provide a loading point that would allow measurement of bending and torsional moment arms from the center of the femoral head to the point of the trochanteric loading.

Mechanical testing was performed on an electrohydraulic materials testing system (Model 1331, Instron Corp., Canton, MA) in stroke control. A displacement rate of 100 mm/second was chosen so that the time to peak force would match the estimated time to peak force in a fall on the hip, or about 30 ms [13]. Actuator displacement and femoral head load were recorded at a sampling rate of 1000 Hz using the system controller (Series 3200, Interlaken Technology Corp., Eden Prairie, MN). After testing, radiographs were repeated for determination of fracture type. Stiffness (0.2% offset), maximum load, and energy absorption capacity (defined as the area under the load-displacement curve to the point of maximum load) were calculated automatically for each specimen. Mechanical test results from one specimen from the younger group were lost due to failure of the test apparatus, so the final groups used for comparing failure properties with densitometric and geometric data consisted of 10 older femurs of mean age 73.1 ± 7.8 (SD) and nine younger femurs of mean age 30.0 ± 11.9 years.

To test whether densitometric and geometric variables taken at the hip correlated with the measured fracture loads, we used the RS1 statistical package (BBN Software Products, Cambridge, MA) to perform bivariate linear regressions between the fracture load and each of the following effect variables: BMD and BMC of the neck and trochanteric regions, and cross-sectional area and moment of inertia at the midneck and intertrochanteric cross-sections. Correlations between fracture load and DXA variables are reported for the combined data from the elderly and young adult femurs.

The contralateral femur from each pair was previously tested in the same loading configuration at a displacement rate of 2 mm/second [10]. We combined the data from the slow tests with the current data to examine the effect of loading rate on the strength and energy absorption capacities of old and young femurs. For these comparisons we used paired data, so the groups included eight pairs of older femurs of mean age 73.5 ± 7.4 (SD) years and nine pairs of younger femurs of mean age 32.7 ± 12.8 years. All data were